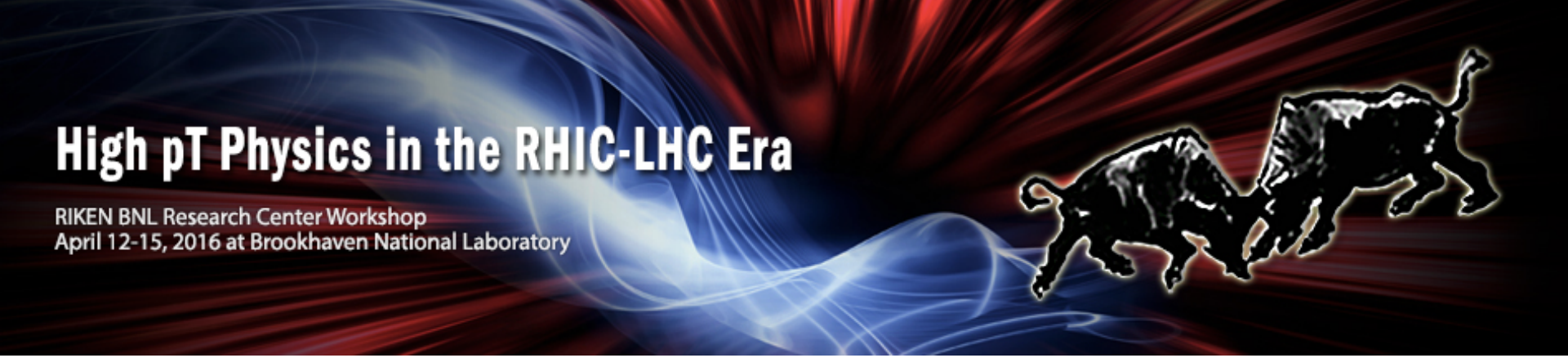


PHENIX results on reconstructed jets in *p*+*p*, *d*+Au, and Cu+Au collisions

Arbin Timilsina (Iowa State University)
for the PHENIX Collaboration

April 13, 2016

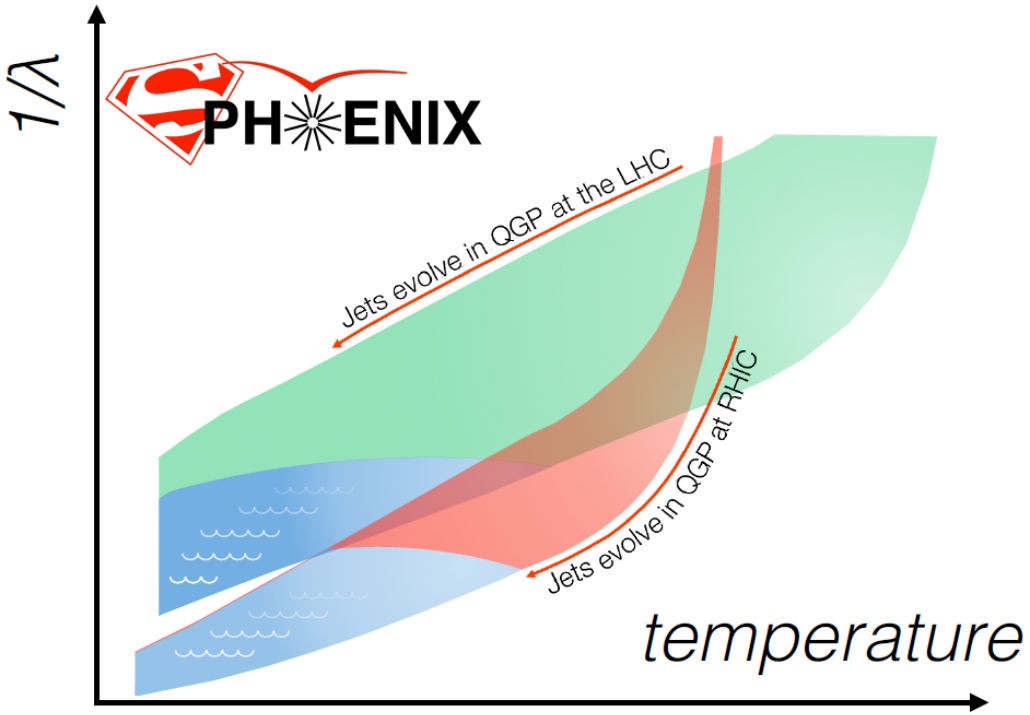
PHENIX

STATE

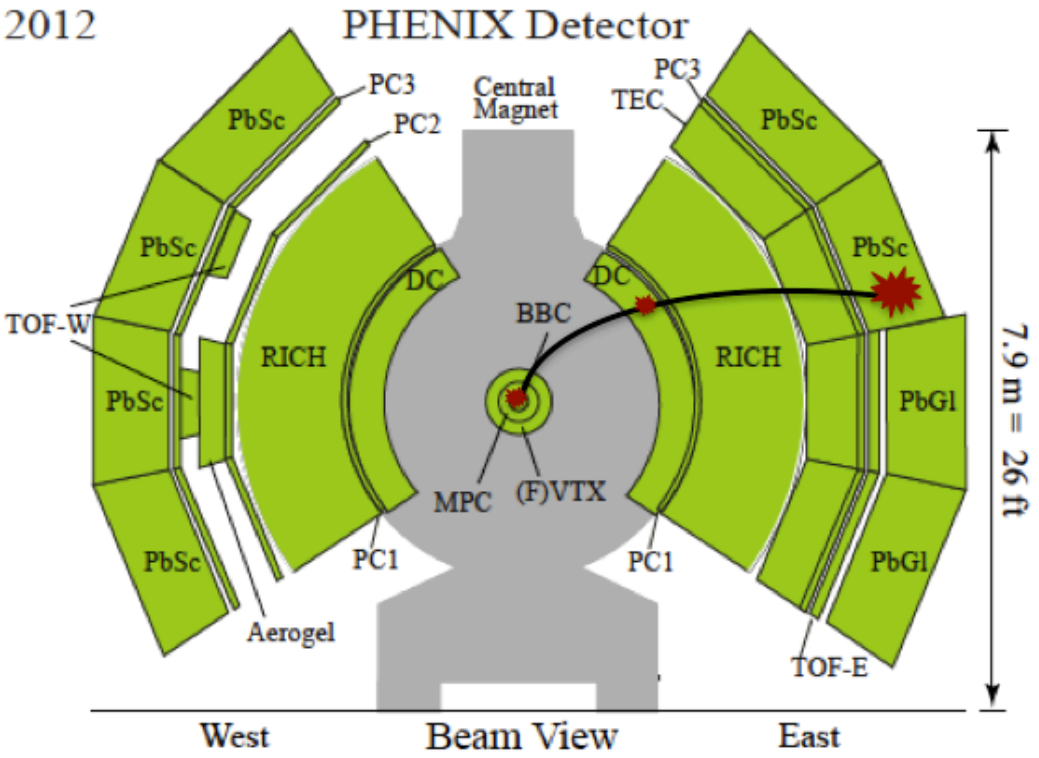
Jets at RHIC

- Versatility of RHIC provides ability to study jet modification in different collision geometries, system sizes, and energy densities

- Jets at RHIC interact with the QGP:
  - for a **larger time fraction**
  - at **larger length scales** in medium
  - at **temperatures closer to T_c**



PHENIX Detector



PHENIX central arms: $|\eta| < 0.35$, $\Delta\phi = \pi$

- Charged particle tracks are reconstructed using the Drift Chamber (DC), the Pad Chamber (PC), and the collision point
- Neutral clusters are measured in the Electromagnetic Calorimeter (EMCal)
- Beam-beam counters ($3.0 < |\eta| < 3.9$) provide vertex, centrality, reaction plane

Jets in PHENIX

- Jets reconstructed using the anti-k_t algorithm
  - EMCal cluster energy + charged particle tracks

- Jet-level requirements
  - number of constituents ≥ 3
  - restriction on contribution of charged constituents
  - jet axis required to be away from detector edge

- Centrality-dependent response matrices generated by embedding PYTHIA *p*+*p* jets into real heavy ion events
  - Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets ≈ 70% of the true jet energy
  - Spectra corrected for detector effects and underlying event fluctuations with unfolding procedure

Jet results from PHENIX

Two new results shown first at Quark Matter 2015

***d*+Au and *p*+*p* jet spectra (2008 data)**

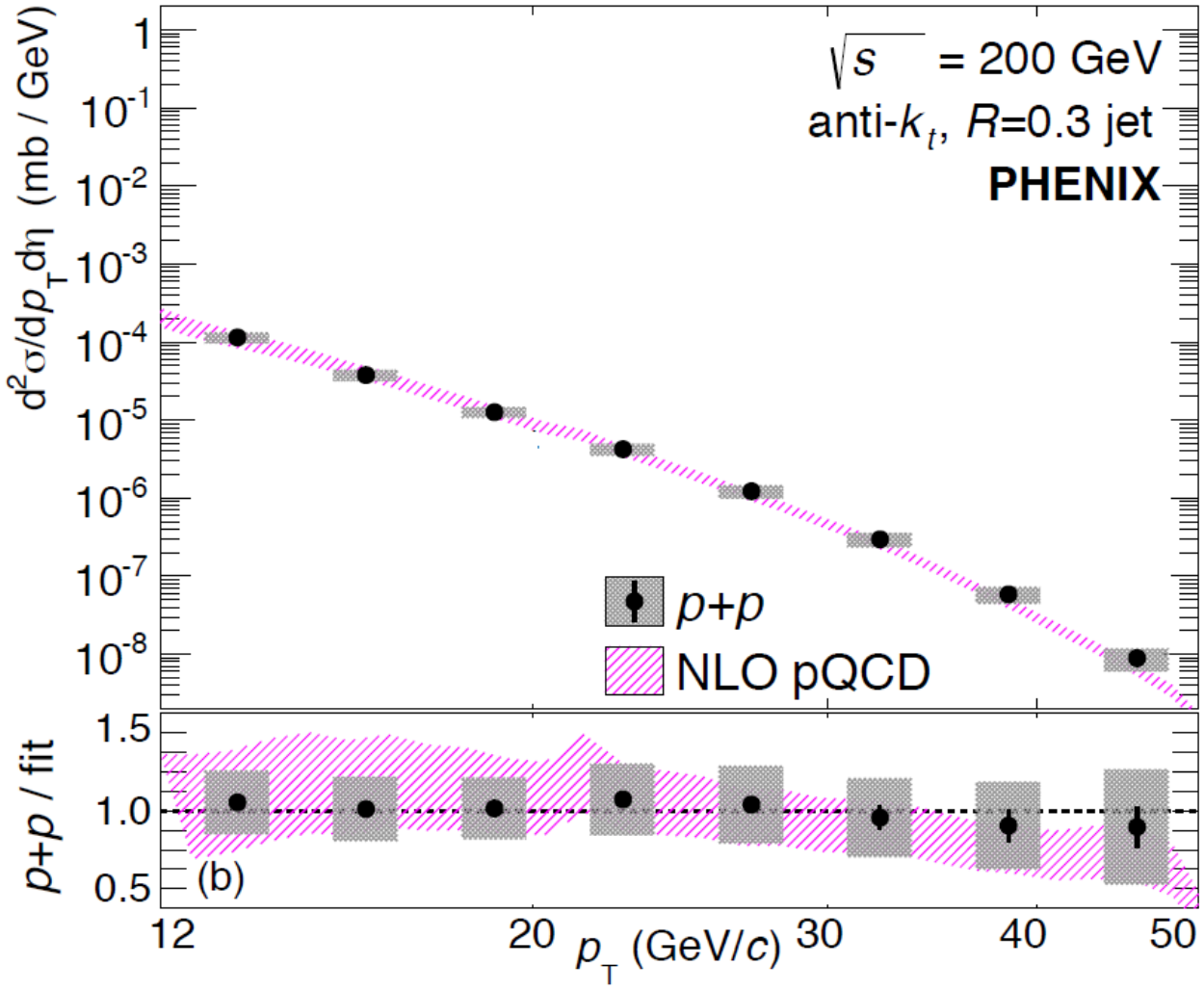
- ***R*=0.3** anti-k_t algorithm
- Phys.Rev.Lett. 116 (2016) no.12, 122301
- Establish pQCD baseline

Cu+Au and *p*+*p* jet spectra (2012 data)

- Preliminary measurement, manuscript being written
- ***R*=0.2** anti-k_t algorithm; choice of smaller cone size due to demands of HI environment
- First look at inclusive suppression of jet spectra by the QGP from PHENIX!

p+*p* collisions

Jet spectra in *p+p* collisions

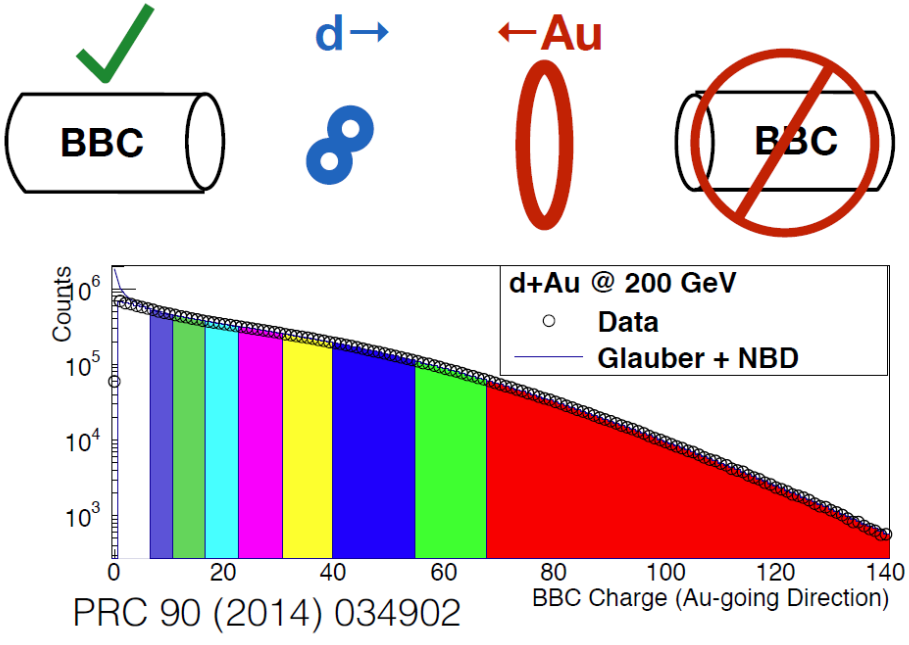


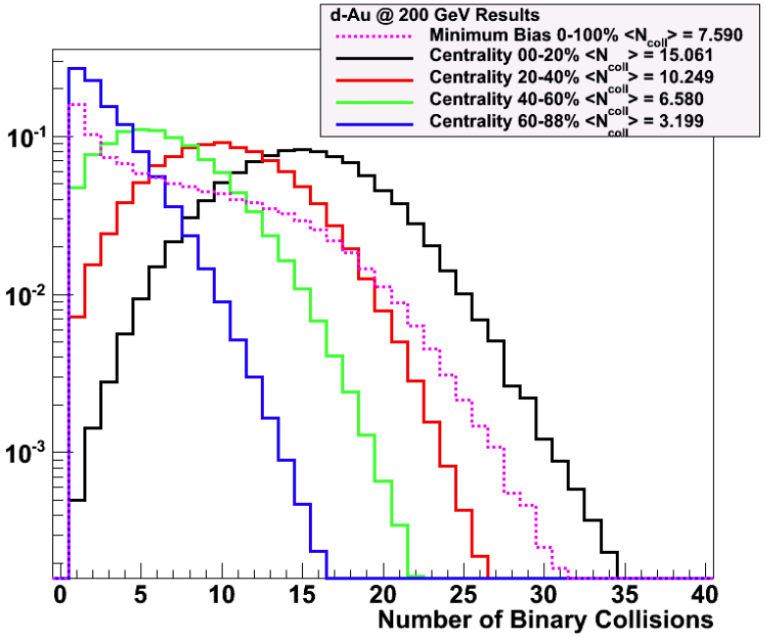
***p+p* spectra**: compare well with **NLO pQCD** calculation

- validates jet reconstruction and correction procedure in PHENIX

d+Au collisions

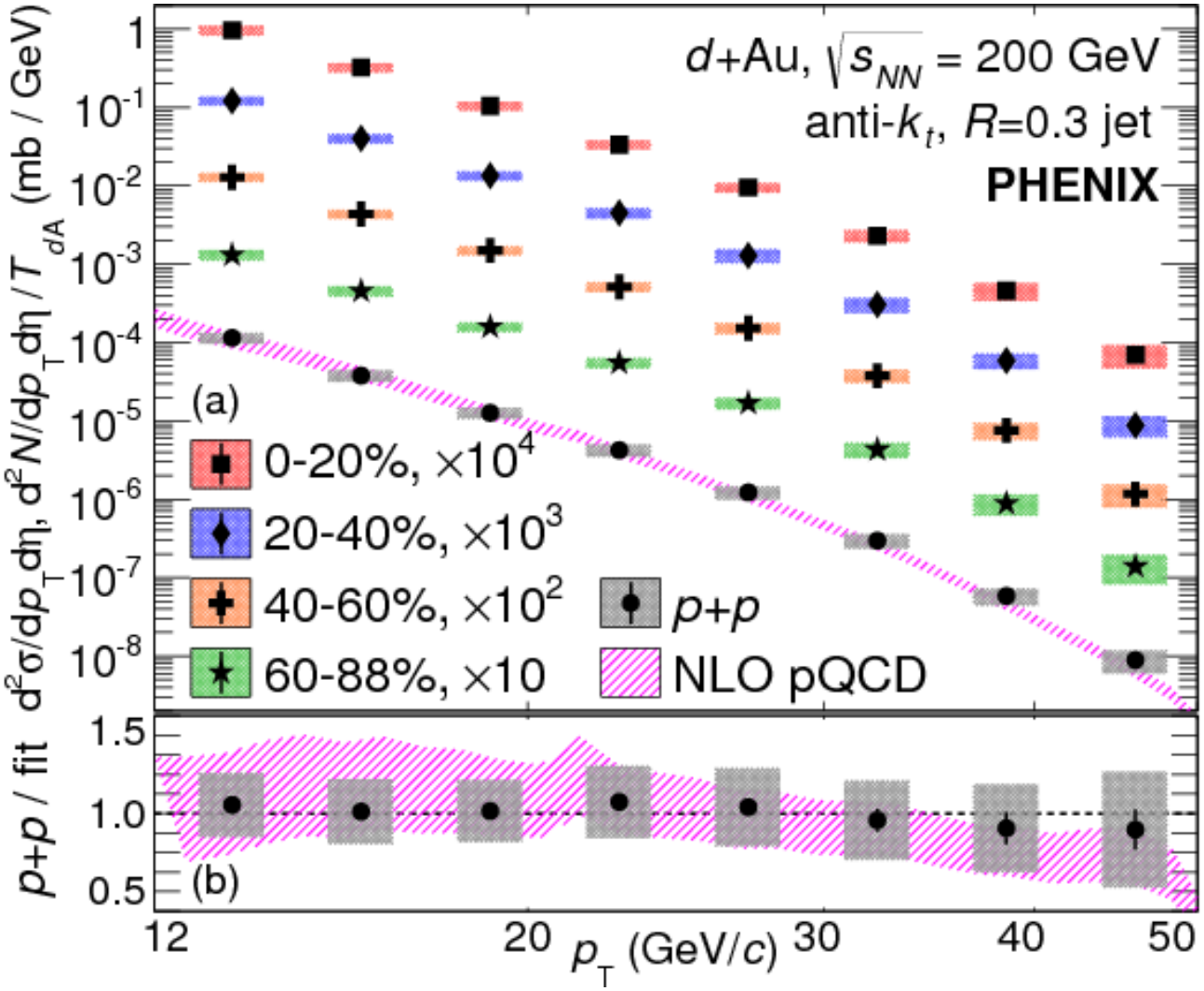
Centrality in *d*+Au collisions





- Selection of centrality categories in *d*+Au collisions based on total charge in Au-going beam-beam counter ($-3.9 < \eta < -3.0$)
- Glauber Monte Carlo simulation to map from the measured charge to geometric quantities
  - estimate nuclear overlap factor T_{dAu} for classes of *d*+Au collisions
  - previously successful with hard and soft observables

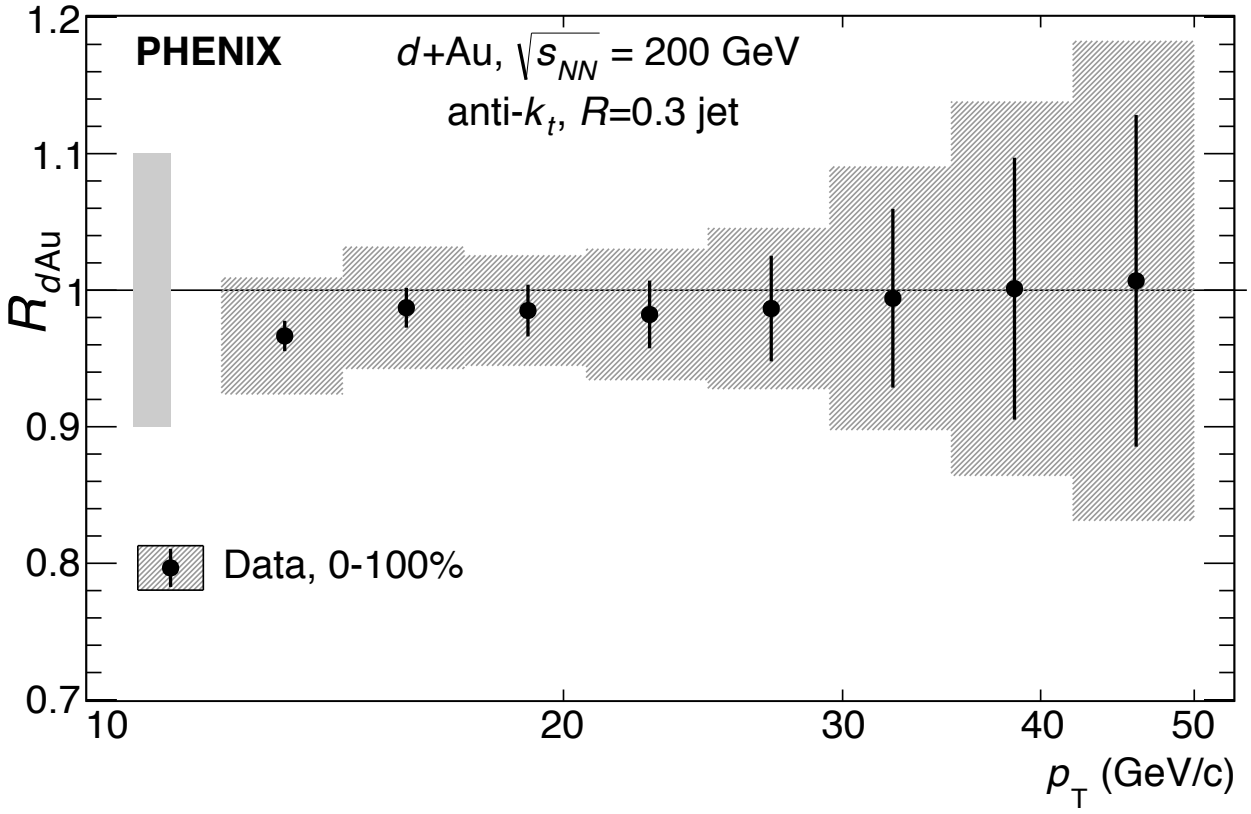
Jet yields in *d*+Au Collisions



***d*+Au per-event yields**: first publication of jet production in asymmetric systems at RHIC

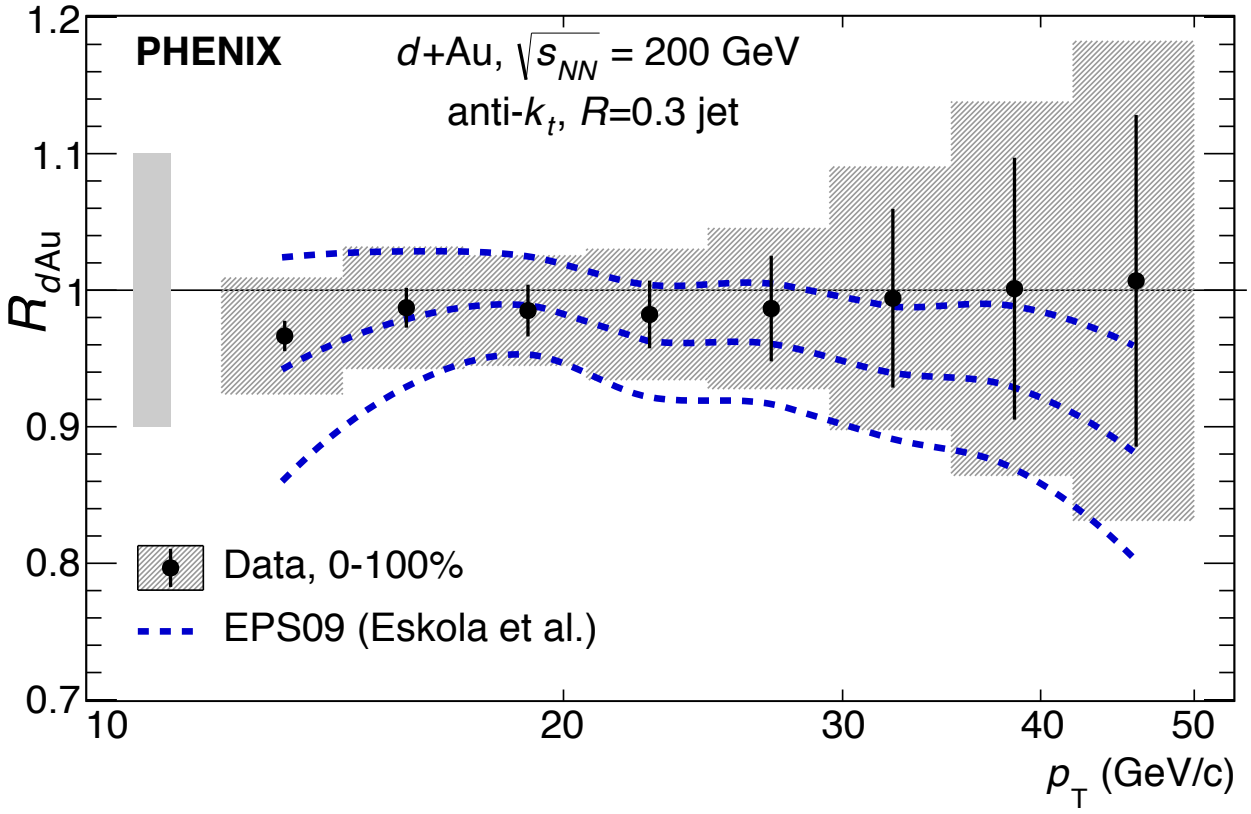
Minimum bias jet rate

$$R_{d\mathrm{Au}} = \frac{\mathrm{d}N^{d+\mathrm{Au}}/\mathrm{d}p_{\mathrm{T}}}{T_{\mathrm{dA}} \times \mathrm{d}\sigma^{p+p}/\mathrm{d}p_{\mathrm{T}}}$$



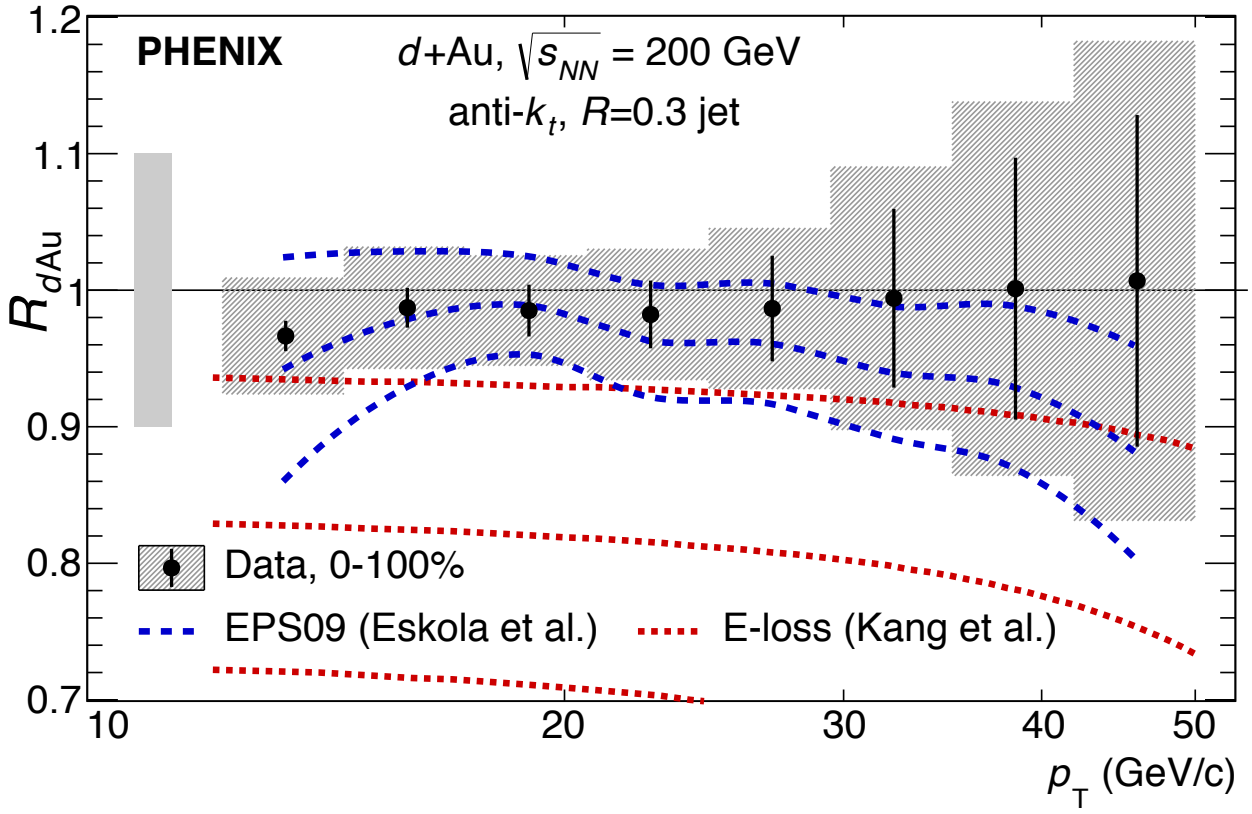
- In centrality-integrated collisions, $R_{d\mathrm{Au}} = 1$

Minimum bias jet rate



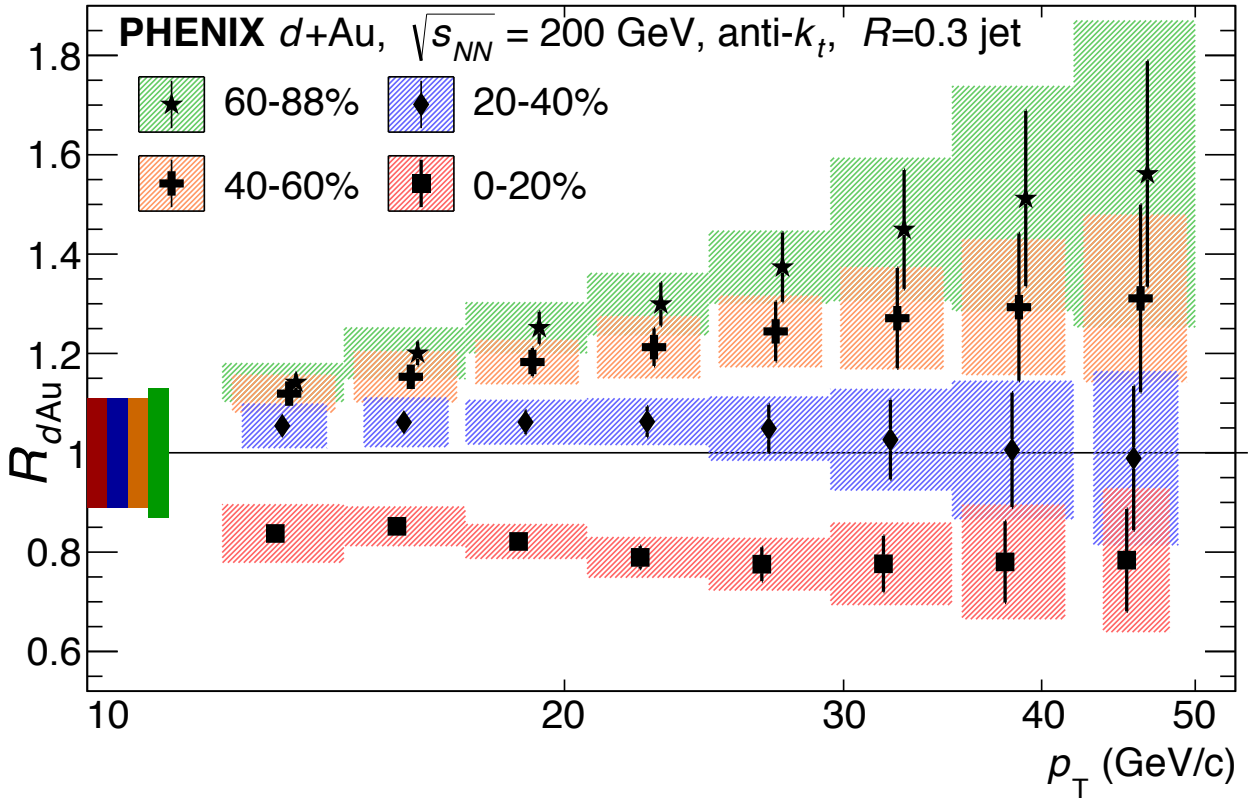
- In centrality-integrated collisions, $R_{dAu} = 1$
  - compares favorably to global nuclear PDF analyses (EPS09) within uncertainties

Minimum bias jet rate



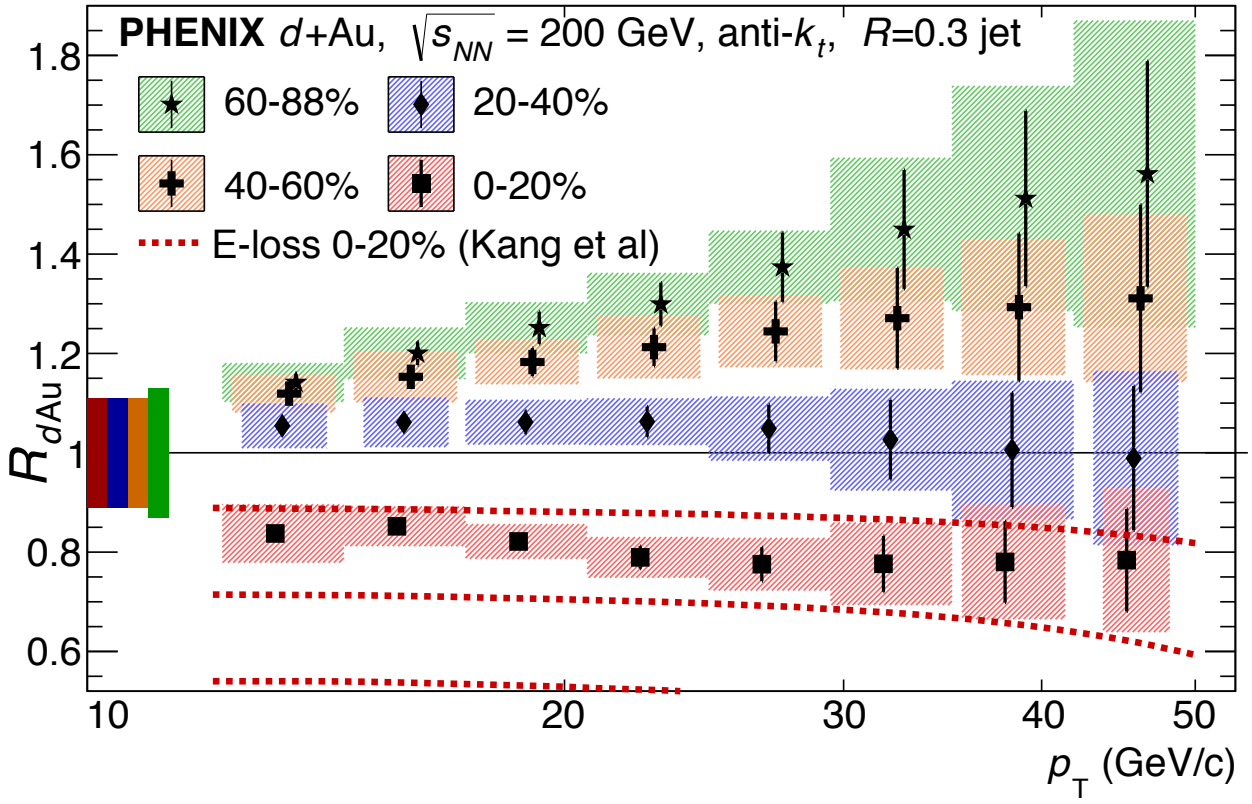
- In centrality-integrated collisions, $R_{dAu} = 1$
  - compares favorably to global nuclear PDF analyzes (EPS09) within uncertainties
  - within initial state E-loss calculations, favors only small momentum transfers between parton and nuclear material

Centrality-selected jet rate



- Suppression of jet rate in central 0-20% (large N_{coll}) events
- Enhancement in 40-60% and 60-88% (small N_{coll}) events

Centrality-selected jet rate



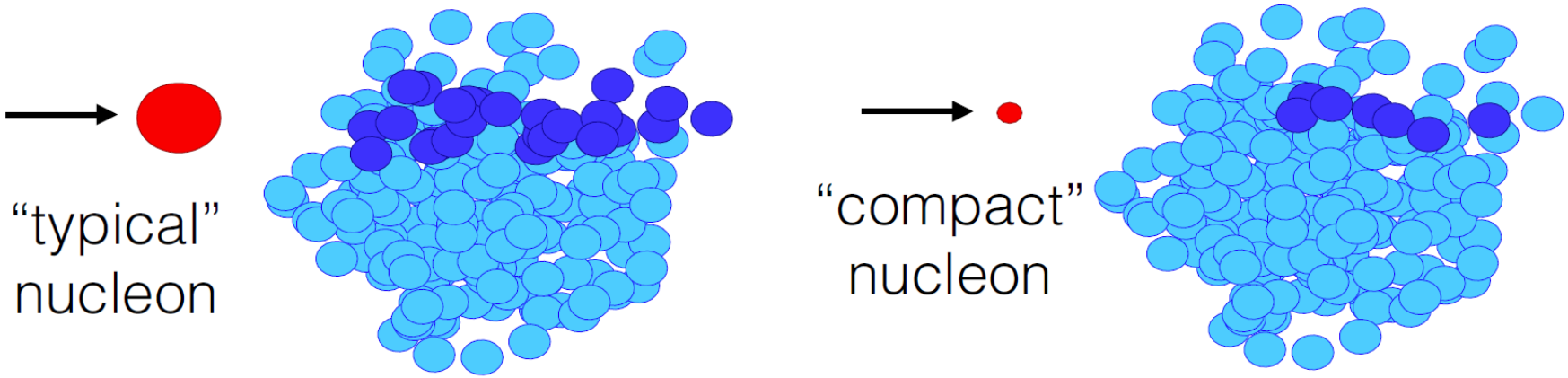
- Suppression of jet rate in central 0-20% (large N_{coll}) events
  - comparable with initial state E-loss calculation
- Enhancement in 40-60% and 60-88% (small N_{coll}) events
  - very challenging to explain within existing frameworks

Reconciling the puzzle

hep-ex/1409.7381
nucl-th/1603.06607

One possibility: "Shrinking proton" picture

- nucleon configuration with a high-x parton (>0.1) are different that "typical" configurations
- interact more weakly than average



Geometric interpretation: as these compact configurations traverse the large nucleus, they strike fewer nucleons

- relative decrease in the N_{coll} distribution
- so peripheral $R_{dAu} > 1$, central $R_{dAu} < 1$

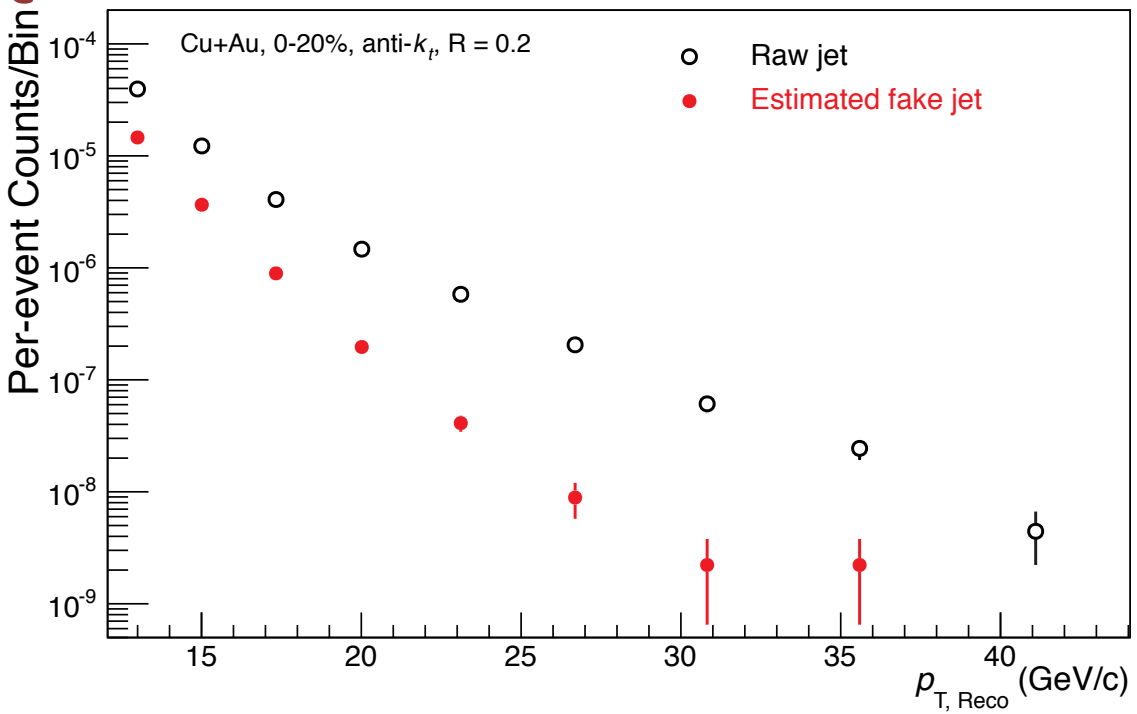
Cu+Au collisions

Cu+Au collisions

Cu+Au comes with challenges

- Stronger underlying event contribution
  -> choice of smaller cone size
- Fake jet contribution
  -> fake jet subtraction

Fake jet

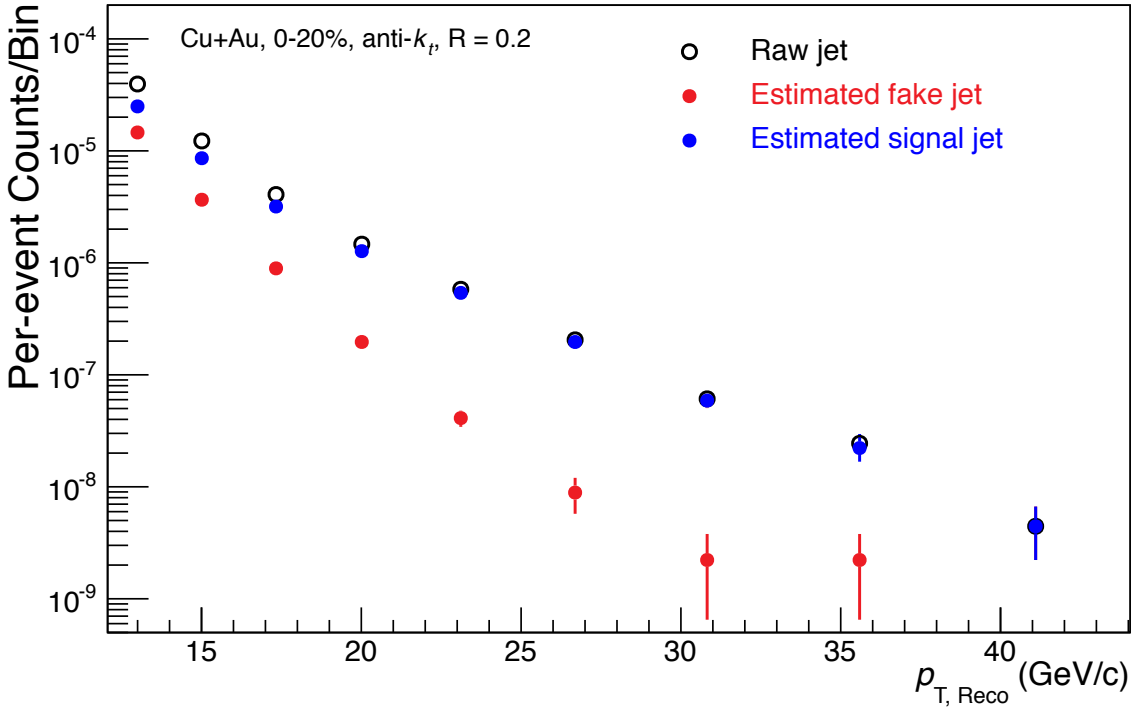


Data driven method of estimating and statistically subtracting fake jet contribution

- For events in which jet is not reconstructed, position (η, ϕ) of tracks and position (η, ϕ) of clusters are randomly shuffled
- Jet reconstruction performed in these shuffled tracks and clusters

  -> returns estimated fake jet

Fake jet

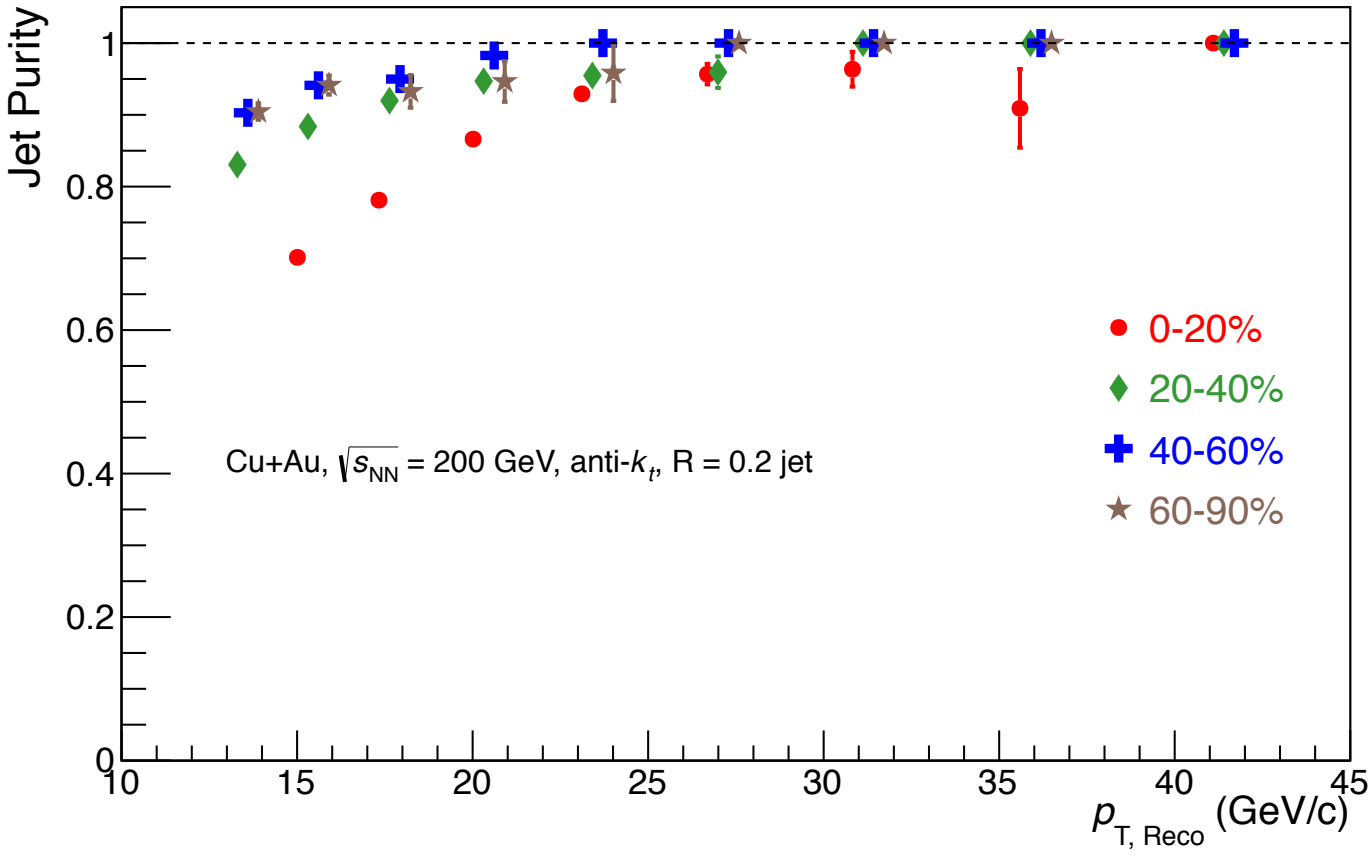


Data driven method of estimating and statistically subtracting fake jet contribution

- For events in which jet is not reconstructed, position (η, ϕ) of tracks and position (η, ϕ) of clusters are randomly shuffled
- Jet reconstruction performed in these shuffled tracks and clusters
  -> returns estimated fake jet
- Estimated fake jet yield is statistically subtracted from the raw jet yield
  -> returns estimated signal jet

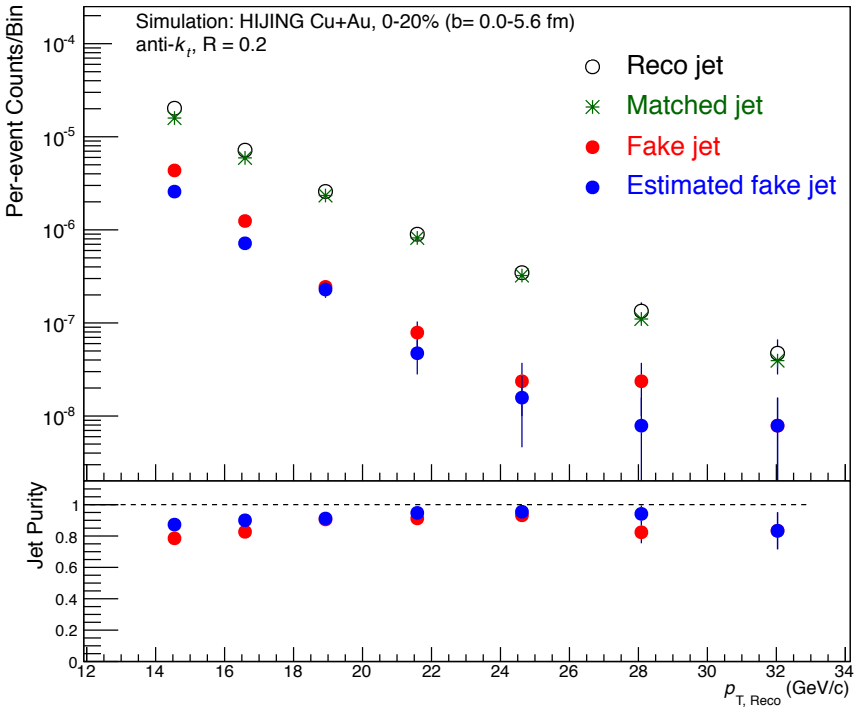
Fake jet

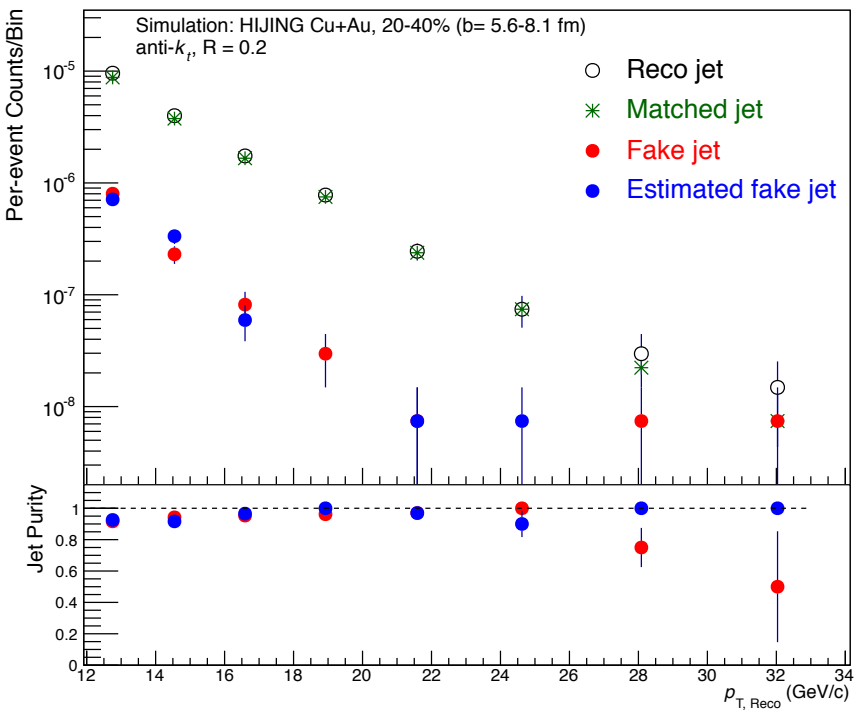
$$\text{Purity} = \frac{\text{Signal jets}}{\text{Raw jets}}$$



- Fake jet contribution is both p_T and centrality dependent; the contribution being largest for central collisions and at low p_T
  - for 0-20%, purity is 70% (93%) at 15 GeV/c (23 GeV/c)

Fake jet HIJING simulation study



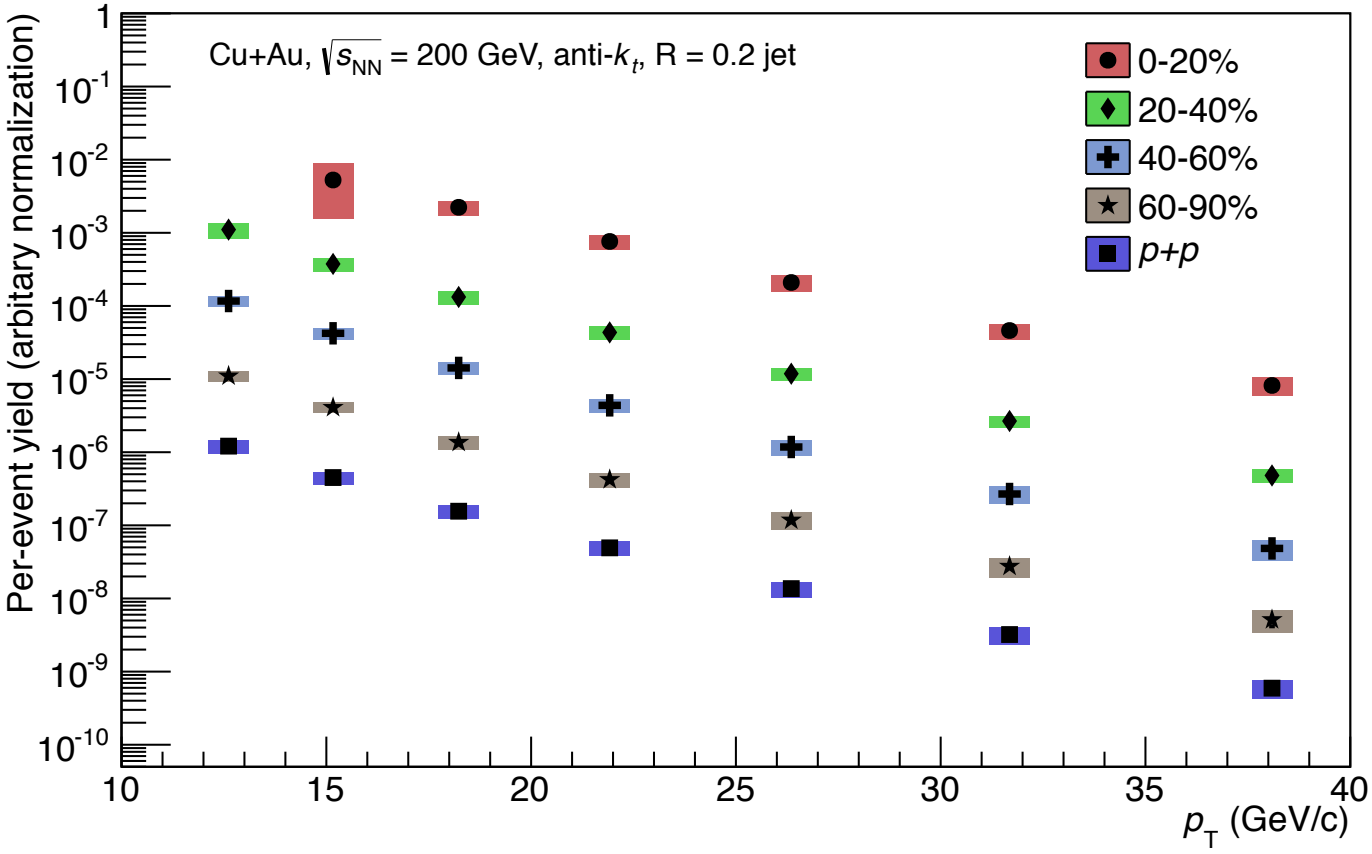


- Matched jet: Reco jet which is within $\Delta R < 0.2$ of true jet
- Fake jet: Reco jet which is not matched

Fake jet estimation procedure gives comparable result!

Fake jet contribution analyzed alternately by re-running the analysis with cluster and track selections of > 2 GeV

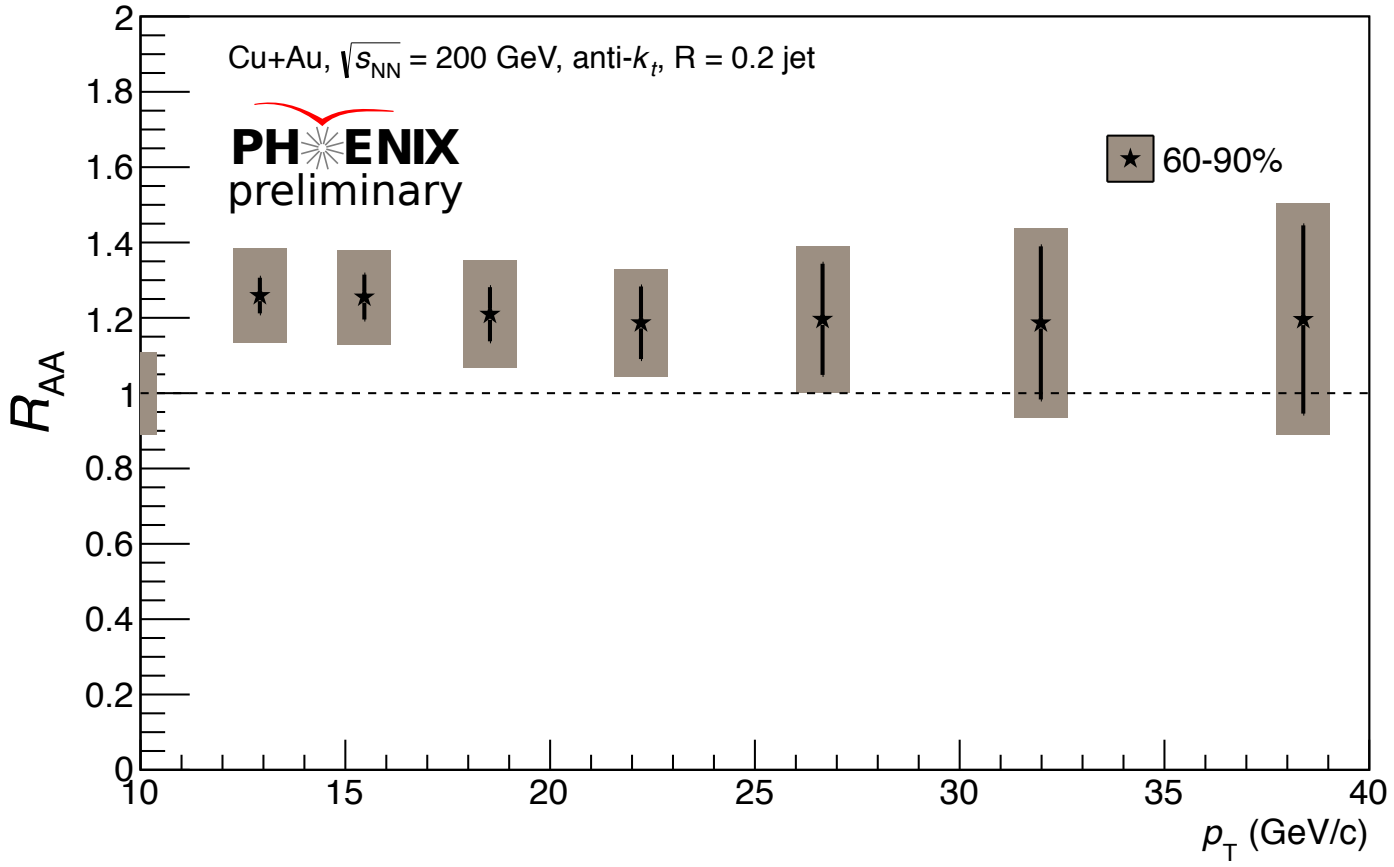
Jet spectra in *p*+*p* and Cu+Au



- Spectra unfolded using SVD method (cross-checked using iterative Bayesian method)
  - detector effects
  - centrality dependent underlying event fluctuations

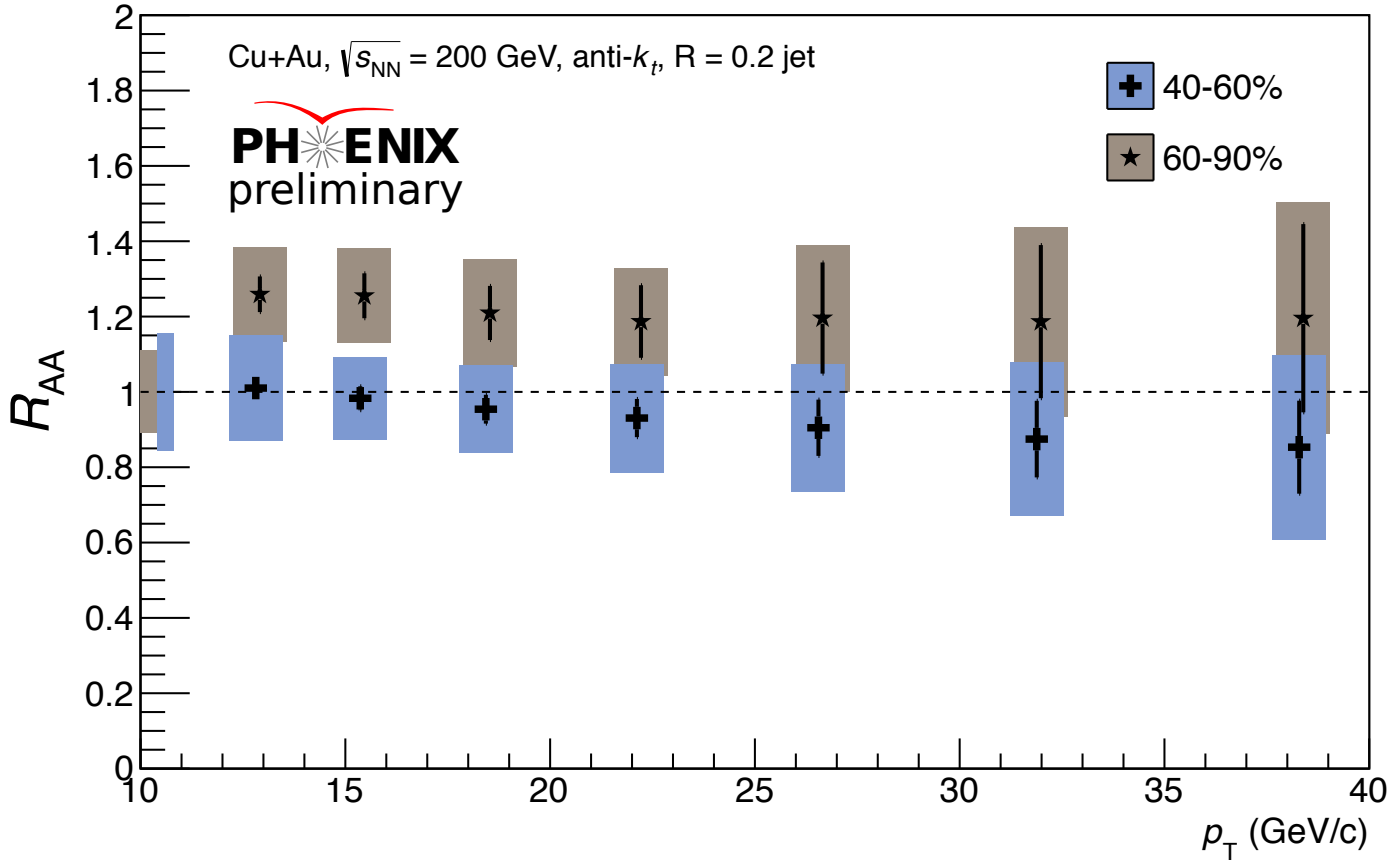
Jet suppression: R_{AA} vs. p_T

$$R_{AA}^{cent} = \frac{\left(\frac{1}{N_{evts}^{cent}} \frac{dN}{dp_T}^{cent}\right)_{CuAu}}{T_{AB}^{cent} \times \frac{d\sigma}{dp_T}}$$



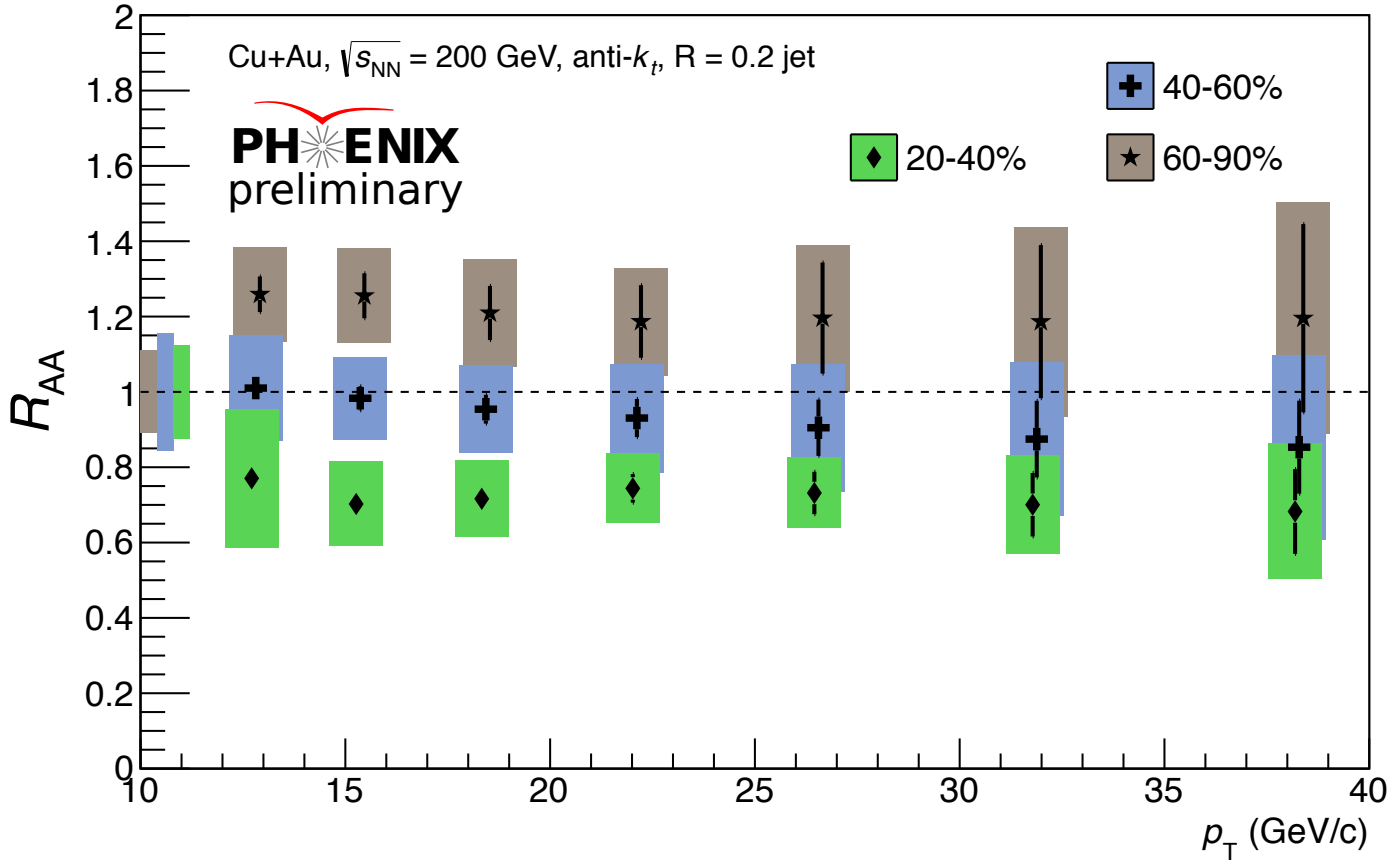
- At high p_T, consistent with 1 within the uncertainties

Jet suppression: R_{AA} vs. p_T



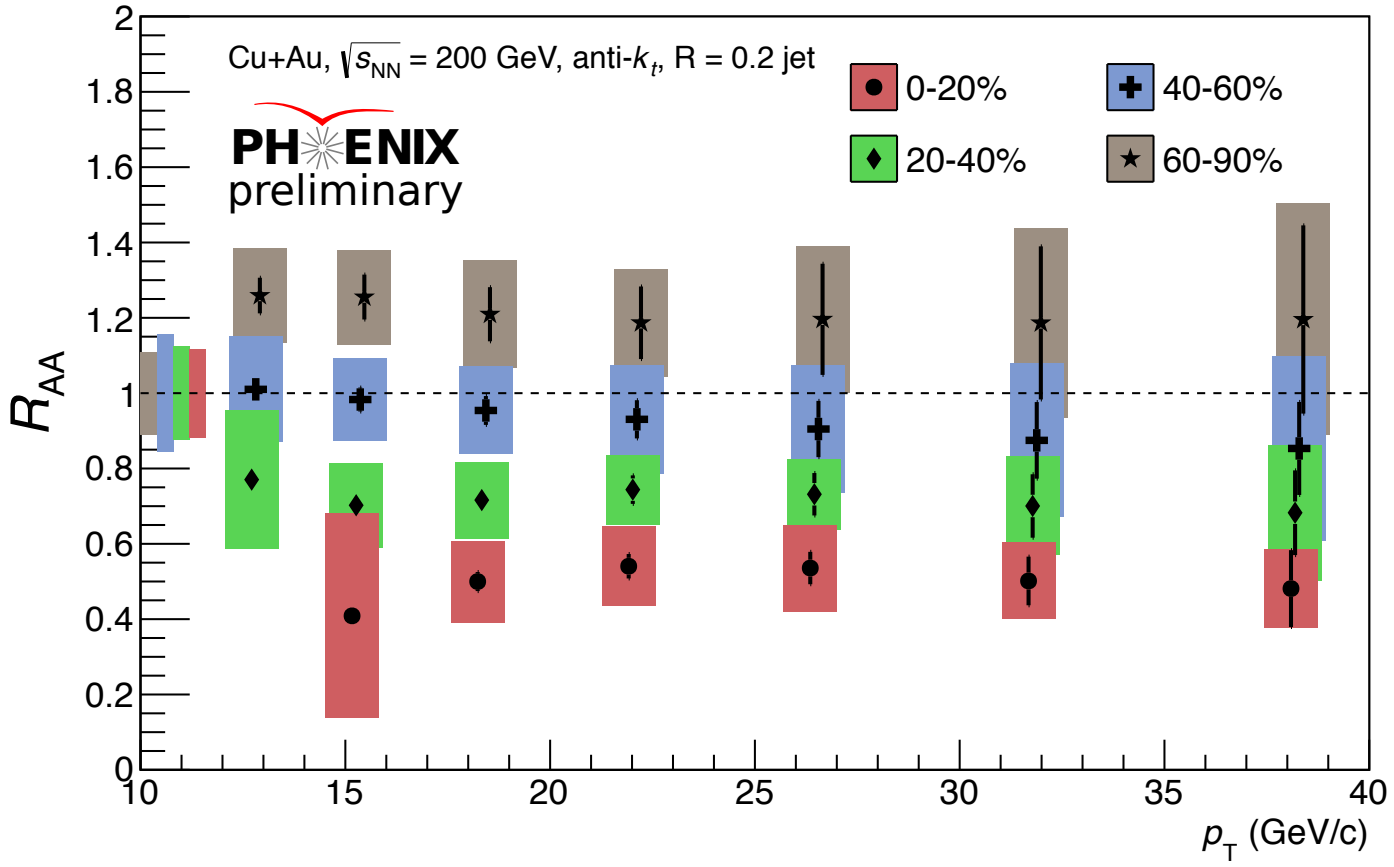
- Suppression shows centrality dependence

Jet suppression: R_{AA} vs. p_T



- Suppression shows centrality dependence
- No p_T dependence

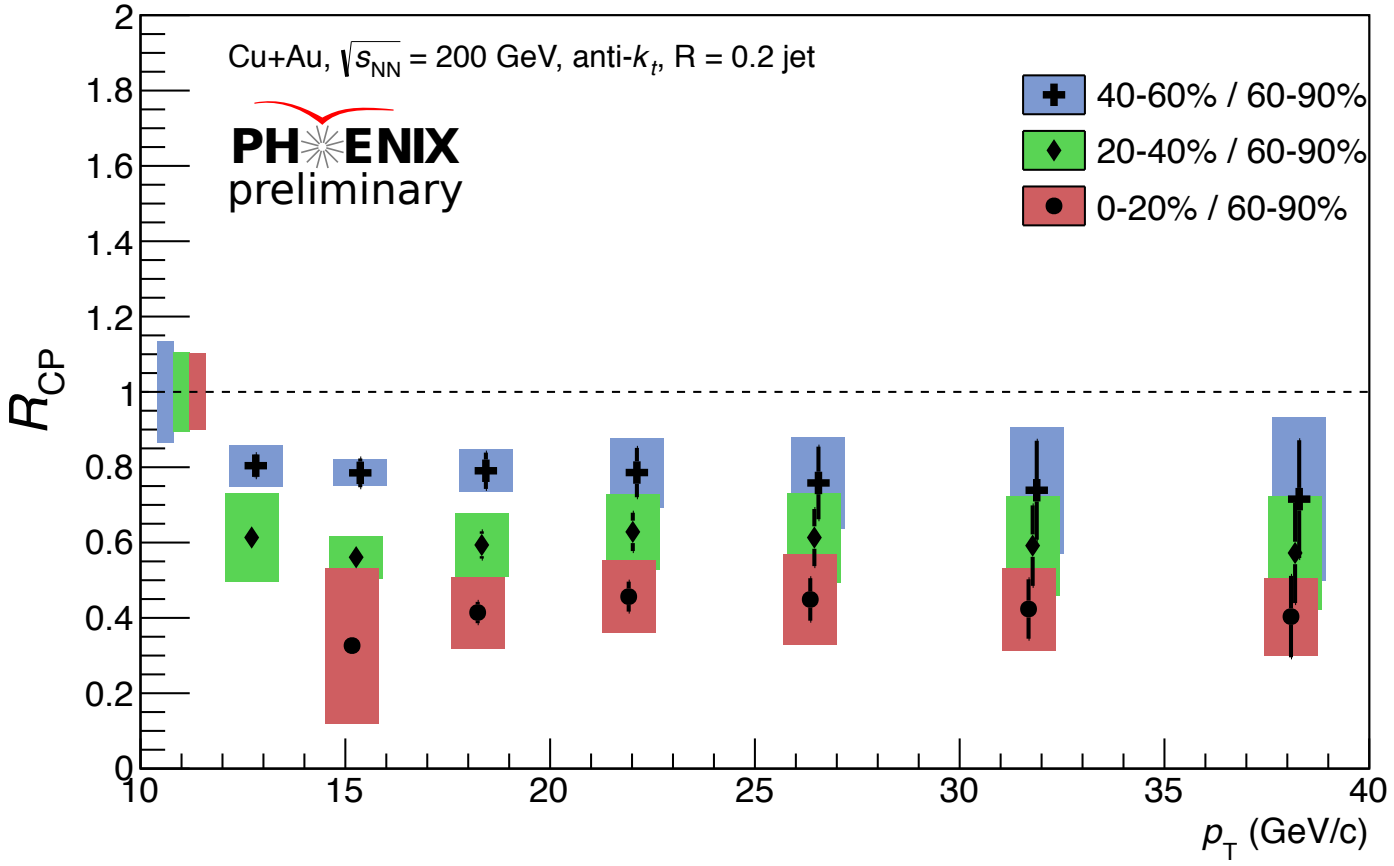
Jet suppression: R_{AA} vs. p_T



- For central collisions, jets are suppressed by approximately a factor of two

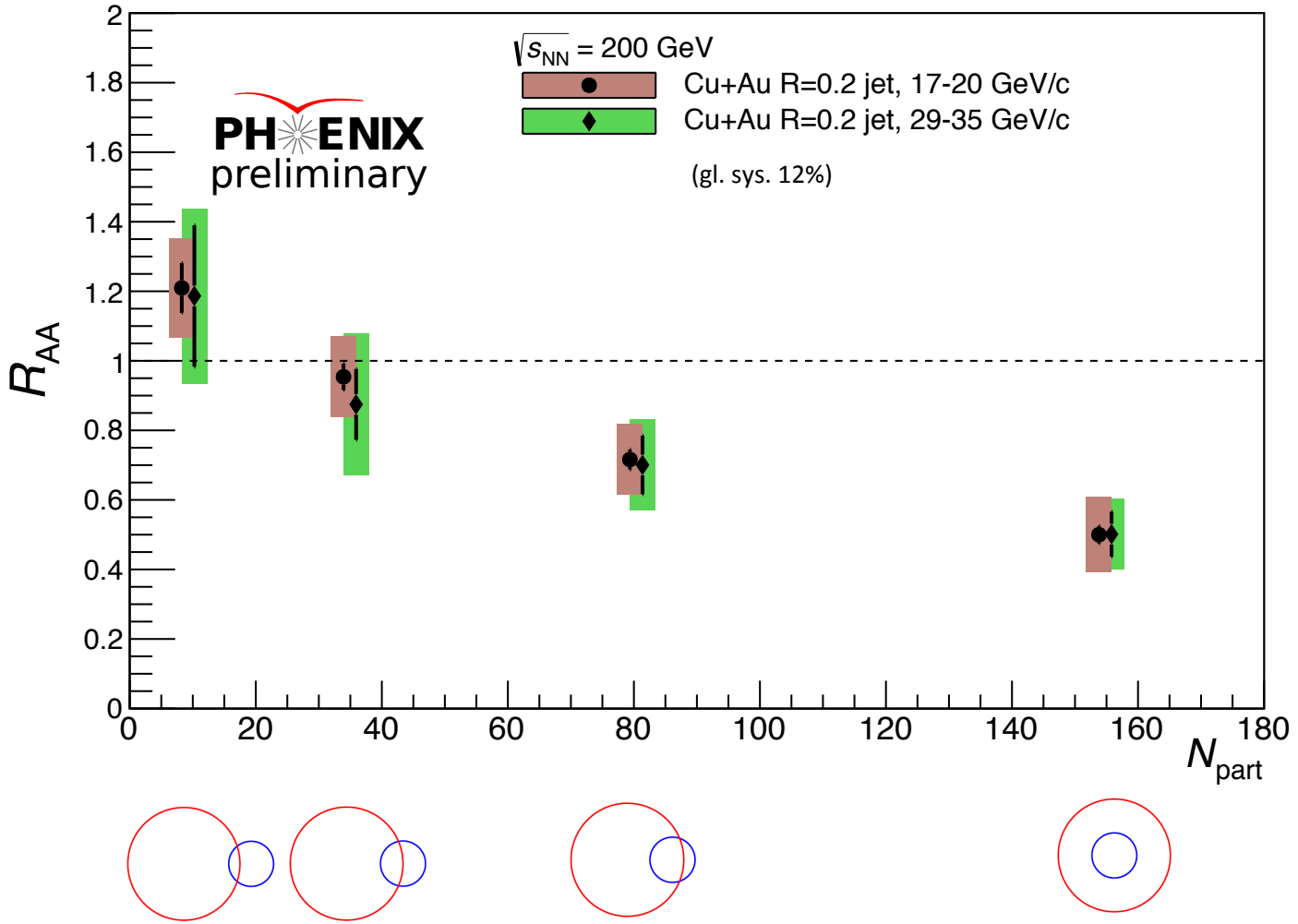
Jet suppression: R_{CP} vs. p_T

$$R_{CP}^{cent} = \frac{\left(\frac{1}{N_{coll}^{cent}}\right)\left(\frac{1}{N_{evts}^{cent}}\frac{dN}{dp_T}^{cent}\right)_{CuAu}}{\left(\frac{1}{N_{coll}^{60\%-90\%}}\right)\left(\frac{1}{N_{evts}^{60\%-90\%}}\frac{dN}{dp_T}^{60\%-90\%}\right)_{CuAu}}$$



- R_{CP} probes relative central vs. peripheral (60-90%) jet production
- Relatively reduced systematics

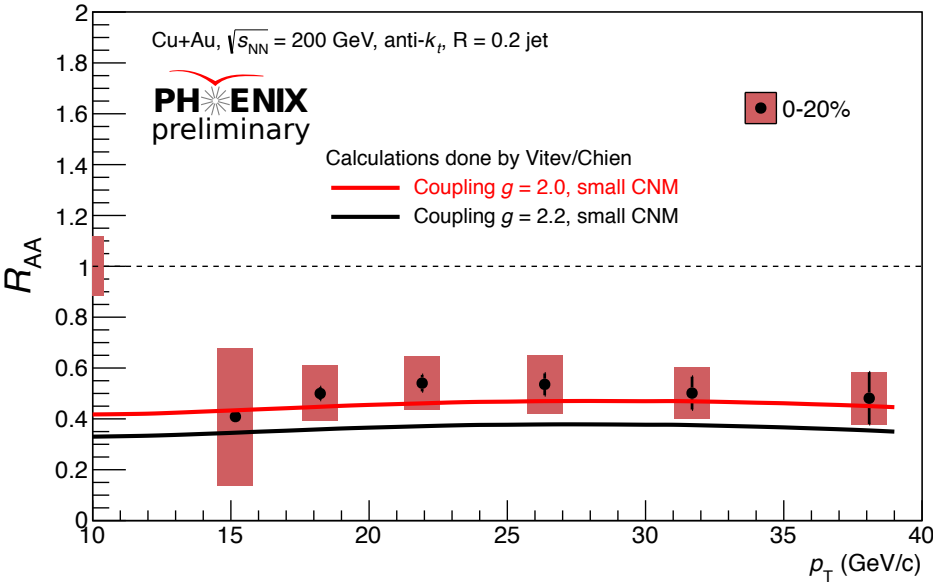
Jet suppression: R_{AA} vs. N_{part}

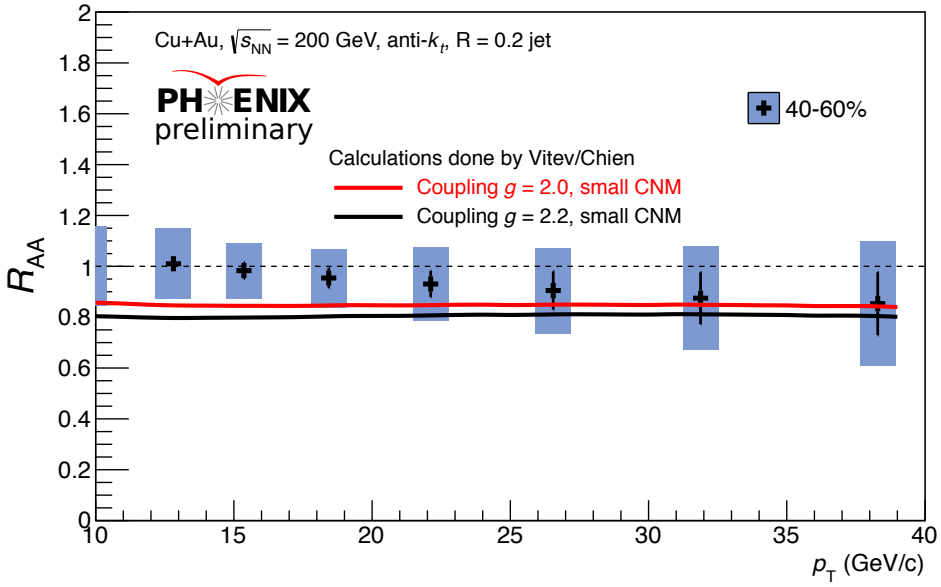


- Another look at the N_{part} dependence of suppression
- No p_T dependence within sensitivity over this kinematic range

Comparisons to theory

hep-ph/1509.07257
hep-ph/1509.02936





- **Left: 0-20%; right: 40-60%**
- SCET$_G$ calculations done for 2 different couplings between the jet and the medium (g=2.0 and g=2.2)
- Quantitatively in line with state-of-the-art jet quenching calculations

Summary

- Progress on jet measurements in small and large systems with PHENIX detector
  - good guidance for future heavy ion jet program at RHIC

- Surprising, unexpected centrality dependence in *d*+Au jet rate
  - one possibility: are we sensitive to the fact that high-*x* nucleons are “smaller” than average?

- Preliminary measurement of a centrality-dependent suppression of jet in Cu+Au collisions
  - jets found to be suppressed by approximately a factor of two in central collisions
  - suppression shows no p_T dependence

Backup

Evaluation of systematic uncertainty

⇒ Variation is made in unfolding procedure. The default data is unfolded with modification in unfolding procedure.

- Shape of input spectrum: The input spectrum is obtained by modifying the power of the truth spectrum by ± 0.5.
- Unfolding is performed with Bayes method (default is SVD method).

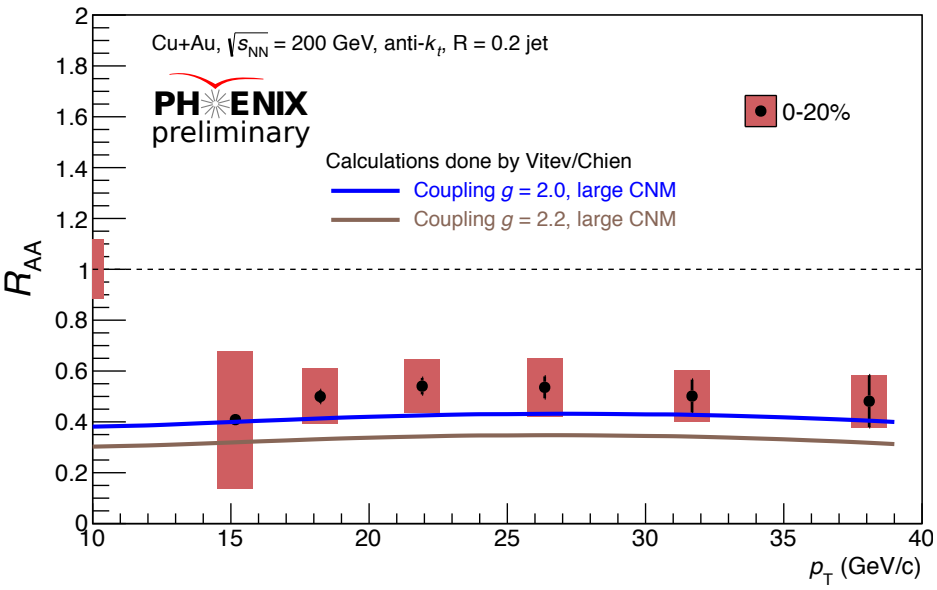
⇒ Variation is made in simulation. The default data is unfolded with modified response matrix.

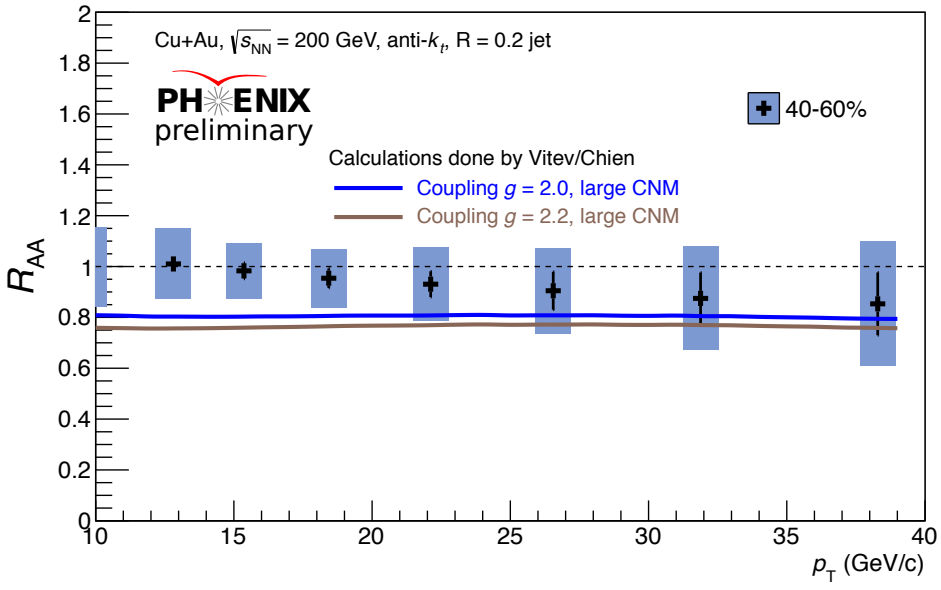
- Energy scale
  - EMCal energy scale: The energy of EMCal clusters is varied by $\pm 3\%$
  - DC p_T scale: The p_T of tracks is varied by p_T dependent way: 2% for $p_T < 10$ GeV/c and increased linearly such that it is 4% at 30 GeV/c.

⇒ Same variation is made in both data and simulation. The modified data is unfolded with modified response matrix.

- Jet-level cuts:
  - Default: $nc >= 3$ && $cf > 0.2$ && $cf < 0.7$. Variation: $nc >= 5$ && $cf > 0.2$ && $cf < 0.6$
- Acceptance
  - Fiducial cut: The reconstructed jets are required to lie within tighter phase space.
  - East/West arm: East arm yield is unfolded with response matrix for east arm and west arm yield is unfolded with response matrix for west arm.
- Fake jet
  - Default: Cluster energy > 0.5 GeV, track $p_T > 0.5$ GeV/c. Variation: Cluster energy > 2.0 GeV, track $p_T > 2.0$ GeV/c.

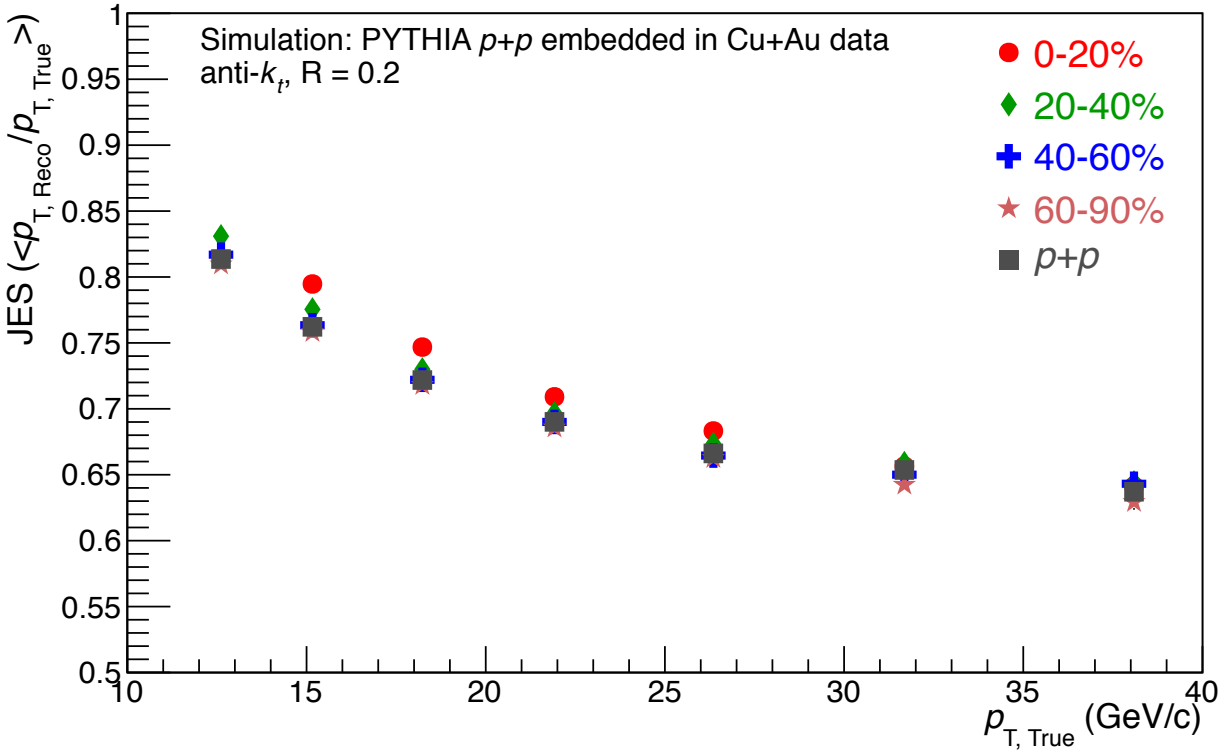
Comparisons to theory





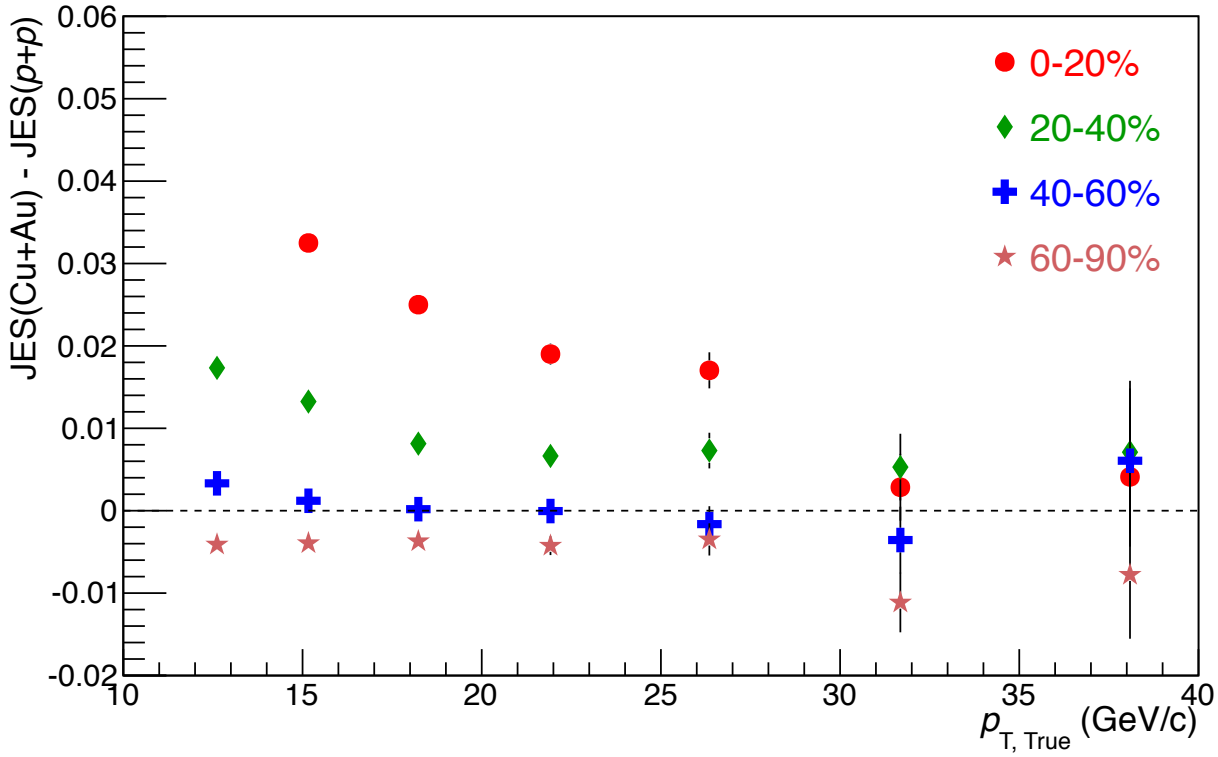
- **Left: 0-20%; right: 40-60%**
- Calculations done for 2 different couplings between the jet and the medium (g=2.0 and g=2.2).

Jets in PHENIX: Jet Energy Scale



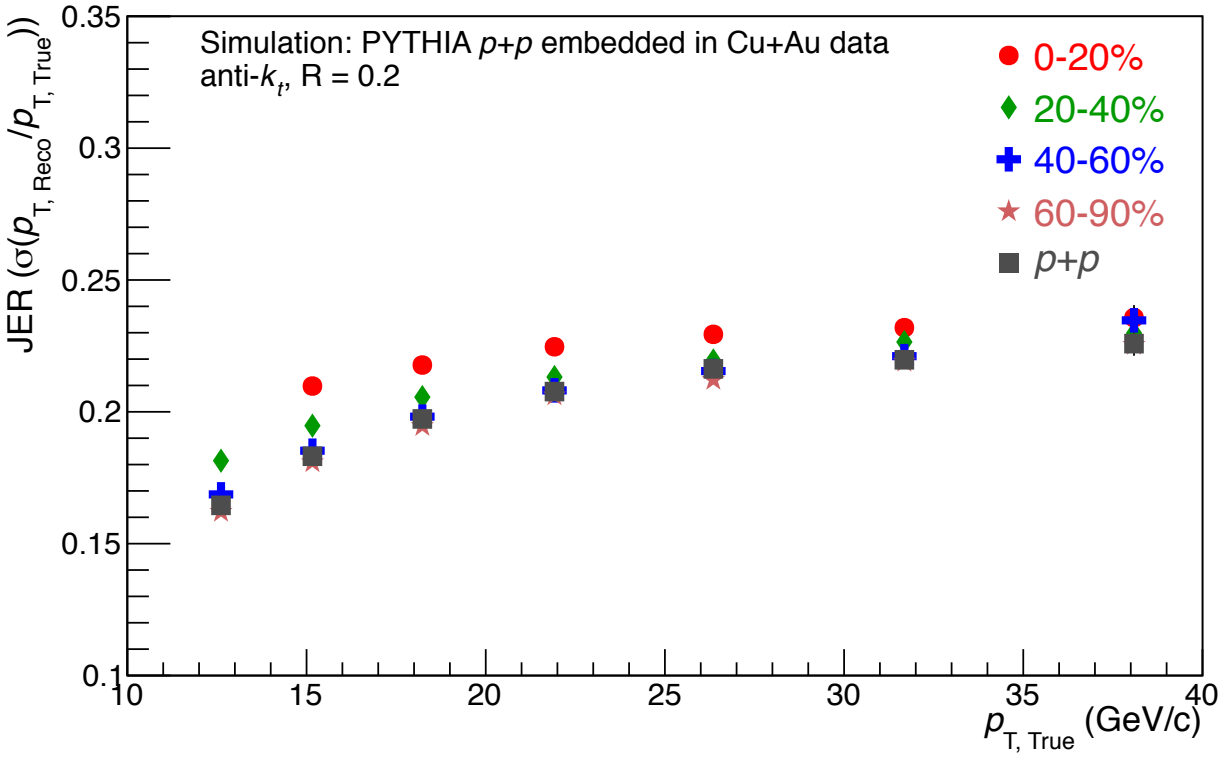
- For each $p_{T,\,True}$ bin, $p_{T,\,Reco}/p_{T,\,True}$ distribution is examined
- Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets ≈70% of the true jet energy

Jets in PHENIX: Jet Energy Scale



- For each $p_{T,\ True}$ bin, $p_{T,\ Reco}/p_{T,\ True}$ distribution is examined
- Due to missing neutral hadronic energy and tracking inefficiency, on average, PHENIX gets ≈70% of the true jet energy
- For 0-20%, the UE increases the $p_{T,\ Reco}$ up to 3.2% (1.7%) at 15 GeV/c (26 GeV/c) relative to that in *p*+*p* events

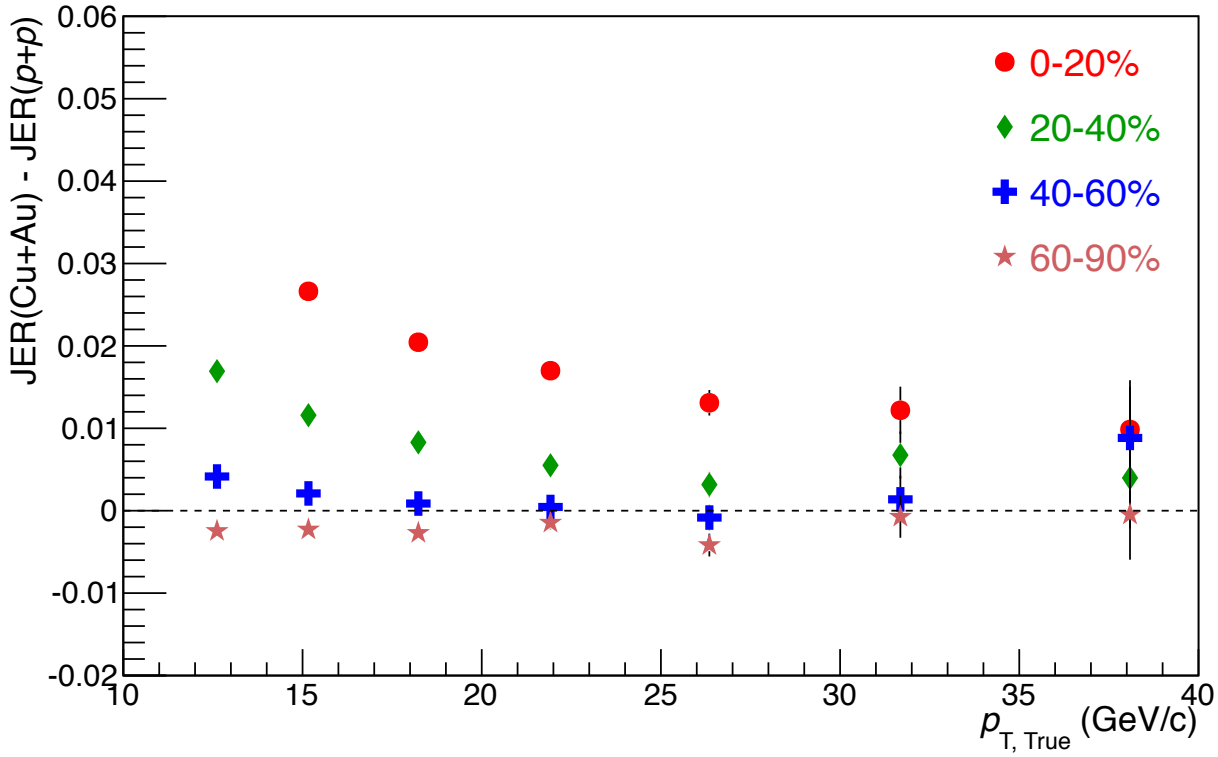
Jets in PHENIX: Jet Energy Resolution



- The width of $p_{T,Reco}/p_{T,True}$ distribution is ≈16-24%

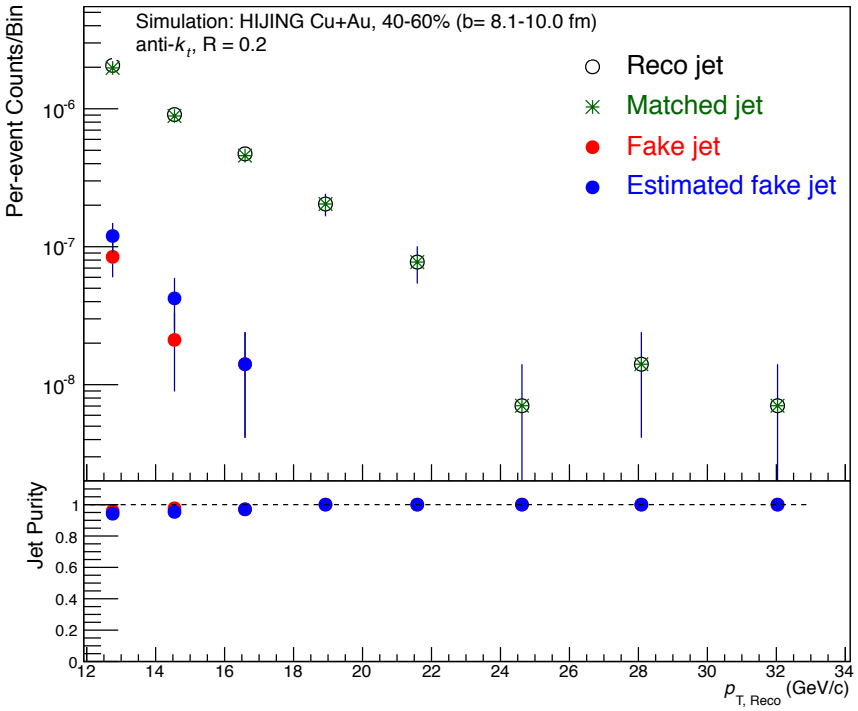
- In PHENIX, the resolution is not driven by EMCal & DC resolution but by jet-by-jet fluctuations

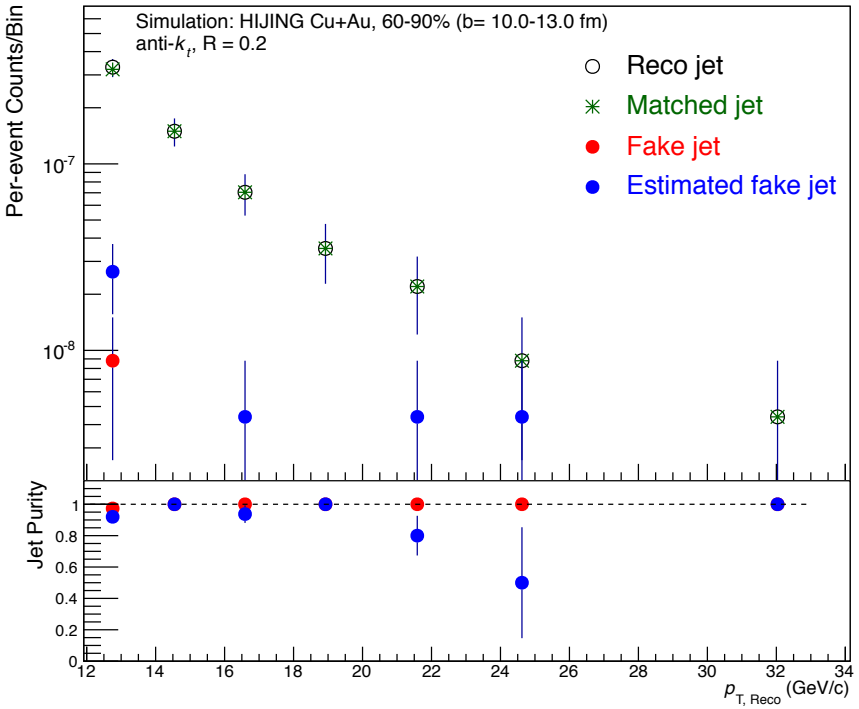
Jets in PHENIX: Jet Energy Resolution



- The width of $p_{T,\ Reco}/p_{T,\ True}$ distribution is ≈16-24%
- In PHENIX, the resolution is not driven by EMCal & DC resolution but by jet-by-jet fluctuations
- For 0-20%, the UE increases the $p_{T,\ Reco}$ resolution up to 2.7% (1.3%) at 15 GeV/c (26 GeV/c) relative to that in *p*+*p* events

Fake jet simulation

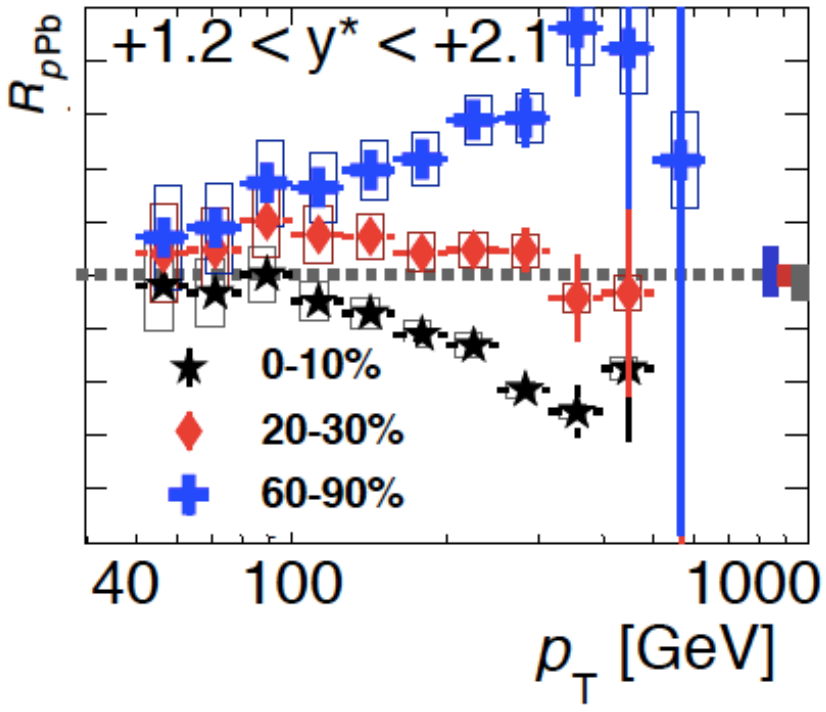


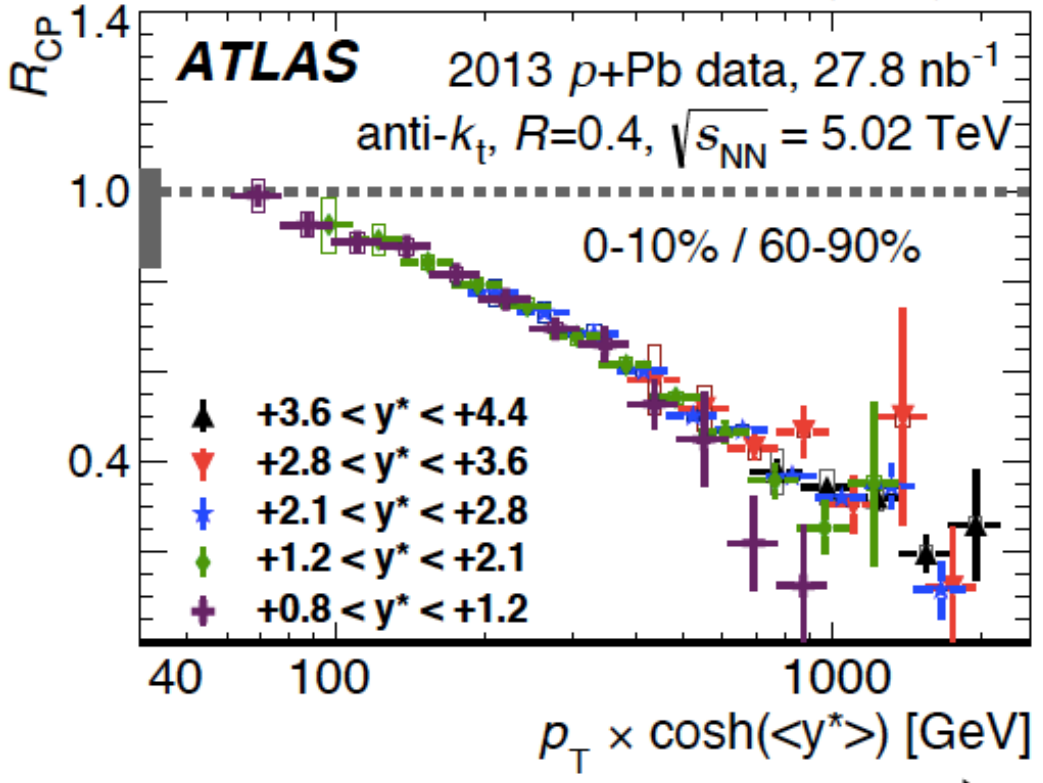


- Matched jet: Reco jet which is within $\Delta R < 0.2$ of true jet
- Fake jet: Reco jet which is not matched

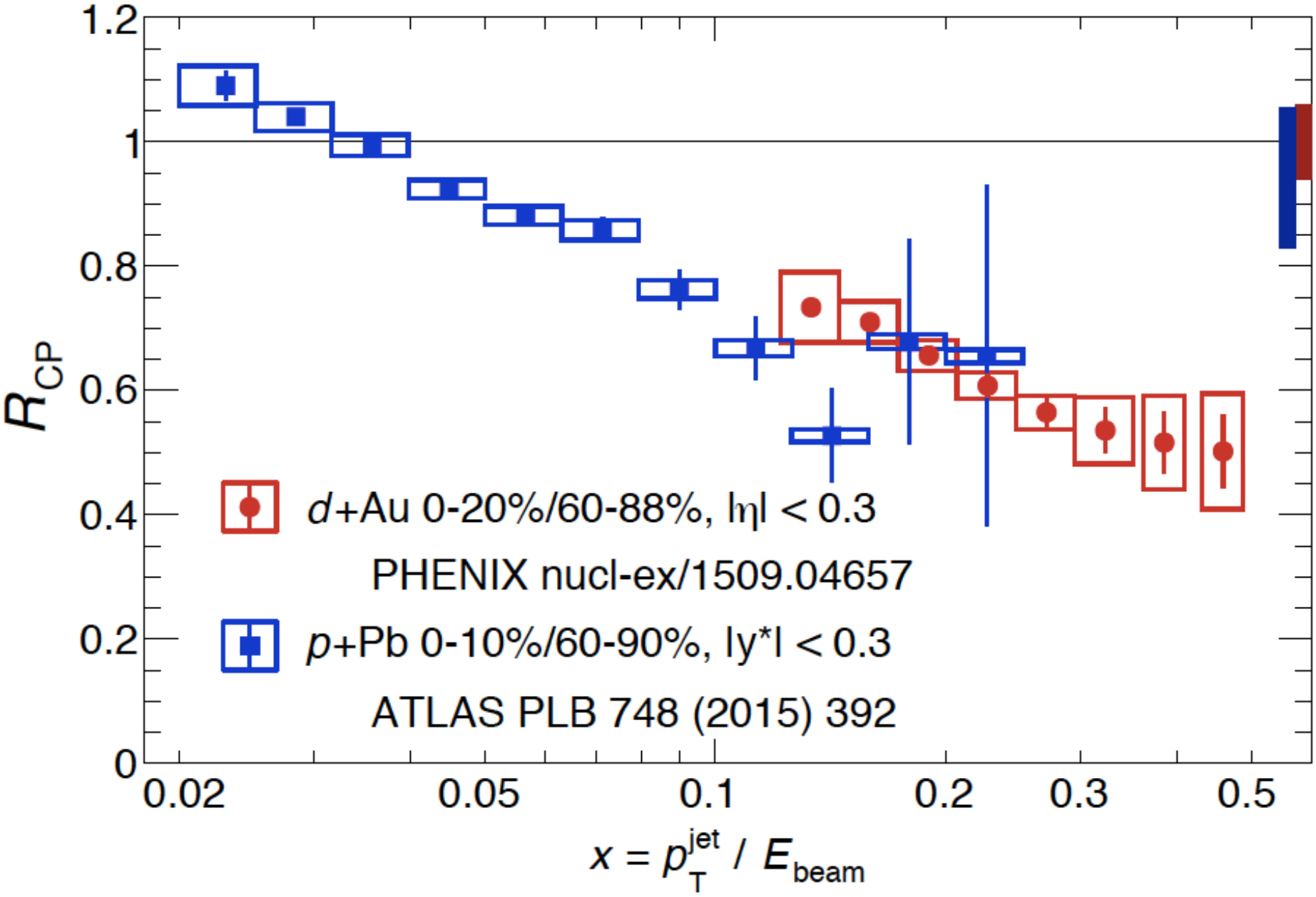
Analogous LHC results

PLB 748 (2015) 392





- Same modification pattern, in the same Bjorken-*x* range
- Modifications to the R_{pPb} / R_{CP} shown to scale only with *proton-x* and not depend on nuclear-*x*



➡ Same (universal) hadron physics at RHIC and the LHC?